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Editors

Separate copies of the colored map by Carpenter, published in this issue, may be obtained (unfolded shipped in tube). Price 25 cents. Remittance should accompany order.

SECRETARY'S NOTE: *Numerical Structure Factor Tables*, by M. J. Buerger (GSA Special Paper 33) has been reprinted and is available at $1.50 per copy (Cloth bound). Remittance should accompany order.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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ISOTOPIC CONSTITUTION OF RADIOGENIC LEADS AND THE MEASUREMENT OF GEOLOGICAL TIME

BY C. B. COLLINS, R. M. FARQUHAR, AND R. D. RUSSELL

ABSTRACT

Isotopic abundances are reported for lead extracted from 1 galena and 96 uranium minerals. The radiogenic leads are mostly from the Athabasca province of the Canadian Shield. Chemical analyses are given for 9 of the uranium-bearing minerals. Ages have been calculated from the radiogenic Pb^{207}/Pb^{206} ratios for all samples with sufficiently low common lead contamination, and from the Pb^{206}/U^{238} ratios for the chemically analyzed samples. These have been used to establish that the Athabasca province was being actively mountain built from 1860 to 1630 million years ago, but not subsequently. It is suggested that the many younger ages determined for the pitchblende deposits in that region are correct and indicate solution and redeposition of the deposits at a later time.

The method of extracting and preparing small quantities of lead as lead tetramethyl for analysis in a mass spectrometer is described.

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INTRODUCTION

The purpose of this paper is to report the results of an investigation of the isotopic constitution of radiogenic leads from uranium deposits. For those radiogenic leads which contained little or no contaminating ordinary lead, ages from the Pb^{207}/Pb^{206} ratio have been listed. Possible errors due to the loss of uranium, lead, or radon from the mineral have been considered.

Fundamentally the measurement of geological time by the lead method is based on the accumulation of the three radiogenic lead isotopes generated in a radioactive mineral by the decay of the two isotopes of uranium and the one thorium isotope. Since we know the rates at which lead is generated from uranium and

thorium (Fig. 1), we can determine the time required for the accumulation of the lead now present in any radioactive mineral which has been analyzed for Pb, U, and Th. If the mineral was free from lead at the time of its formation, and if it has remained unaltered except for the decay of uranium and thorium to lead, then the time so computed is the absolute age of the mineral. Chemical methods do not distinguish between radiogenic lead produced by uranium or thorium decay and ordinary lead not of radiogenic origin which may have been present initially. A further difficulty arises because of possible leaching of uranium or thorium or lead from the mineral. Radioactive minerals have usually been cracked by the escape of helium so that water may easily have entered.

However, if the lead has been analyzed both chemically and isotopically three independent calculations of the age of the mineral are possible, from the ratios of:

(1) Pb^{208}/Th^{232}
(2) Pb^{206}/U^{238}
(3) Pb^{207}/Pb^{206}

A fourth age may be calculated from the Pb^{207}/U^{235} ratio, but it is not independent of the ages obtained from (2) and (3).

Age determinations based on method (3) (Nier, 1939) are convenient because no chemical analyses are required. A correction may be made for the presence of ordinary lead on the basis of lead of mass number 204 (Fig. 2), which is not generated by the decay of uranium or thorium. Furthermore, leaching of lead or uranium from a mineral does not seriously affect the ages obtained by method (3) in many cases, because leaching would affect all the isotopes of any one element equally and would not affect the ratio Pb^{207}/Pb^{206} by any large amount.

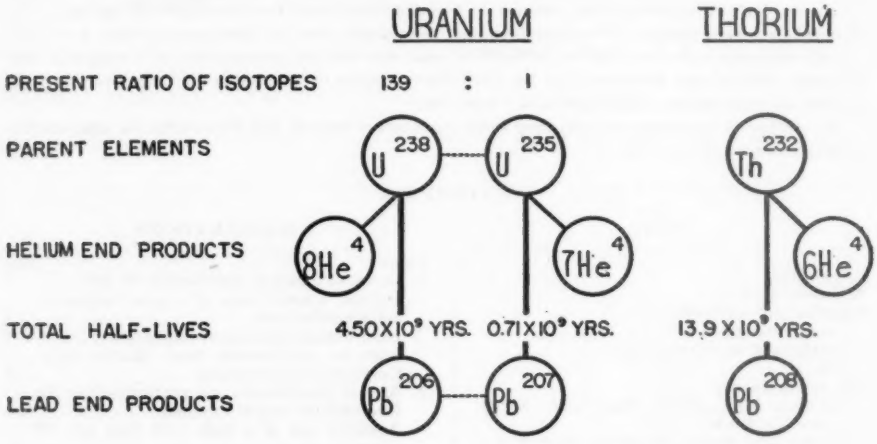

FIGURE 1. DECAY OF URANIUM AND THORIUM TO LEAD

ACKNOWLEDGMENTS

The authors wish to thank the geologists who sent us samples for analysis, and especially those who took trouble to collect or concentrate material. We are grateful to the National Chemical Research Laboratories, England, for chemical analyses, and to E. C. Bullard and F. H. Burstall who arranged to have these analyses made. We are indebted to Professor J. T. Wilson for his assistance in this research and for critically reading this paper, and to Dorothy Perryman, David Beuk, and John Kenyon for technical assistance. We acknowledge the financial support of the National Research Council of Canada, the Geological Survey of Canada, the Research Council of Ontario, and Imperial Oil Limited.

Experimental Methods

General Statement

The greatest need in determining geological ages by radioactive methods is more experimental data. Age determinations by the lead

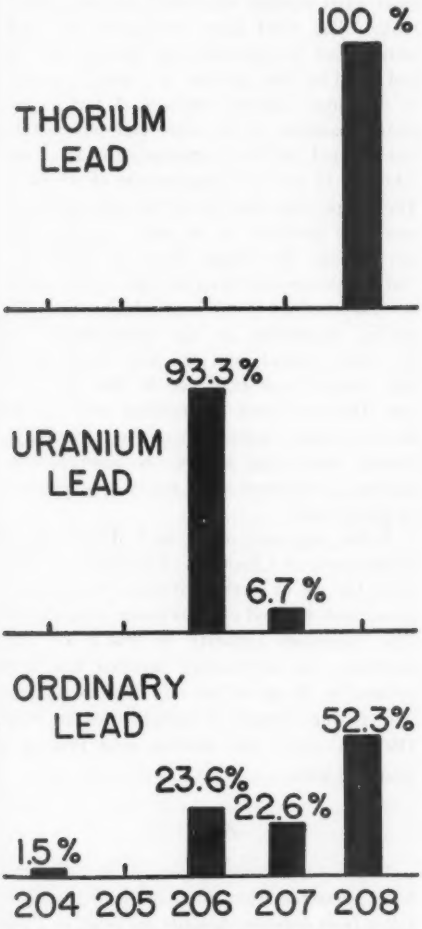

Figure 2. Isotopic Constitutions of Typical Radiogenic and Common Leads

method were firmly established by the outstanding work of Nier (1939) who reported a substantial number of ages from both chemical and isotopic analyses of radiogenic leads, and who pointed out that ages based on the ratio of radiogenic Pb^{207}/Pb^{206} were the most reliable. It was also evident from Nier's investigation that the only reliable measure of ordinary lead contamination in uranium and thorium minerals was from an isotopic analysis of the lead present. In 1939 very few laboratories had the necessary equipment and qualified personnel to do such analyses. Now mass spectrometers are available which have sufficient resolution to separate the lead isotopes, and a new technique has greatly simplified the actual analysis.

It is possible to determine the relative abundances of the isotopes of lead from mass spectrograms of lead prepared as lead tetramethyl which can be introduced into the mass spectrometer as a gas. Analyses may be made quickly. There is no memory effect in the instrument from the preceding sample; a radiogenic lead spectrogram showed no contamination from an ordinary lead sample analyzed 60 minutes previously. Careful chemical purification of the lead is not necessary with the result that most of the work can be done by a technician. The determination of the relative abundances of the lead isotopes from spectrograms of lead tetramethyl has been reported by Collins, Freeman, and Wilson (1951), Collins, Russell, and Farquhar (1953, p. 403), and by Dibeler and Mohler (1951).

Synthesis of Lead Tetramethyl

The synthesis of lead tetramethyl from lead chloride and Grignard reagent has been described by Jones and Werner (1918, p. 1273). The term Grignard reagent refers to any solution of an alkyl magnesium halide in absolute ether. A solution of methyl magnesium bromide in dry diethyl ether is satisfactory for the preparation of lead tetramethyl. The bromide forms the most stable solution and has sufficient reactivity for this application.

The Grignard reagent was prepared by bubbling dry methyl bromide vapor through a mixture of magnesium turnings and absolute ether. The reaction took place under a nitrogen atmosphere with continuous stirring and refluxing of the components to insure complete solution. The resultant clear liquid was maintained under partial vacuum for 24 hours to remove any excess dissolved methyl bromide.

Although the solution was extremely reactive and slightly unstable, quantities could be stored for as long as 6 months in sealed containers under a dry nitrogen atmosphere if precautions were observed to shield the reagent from direct sunlight.

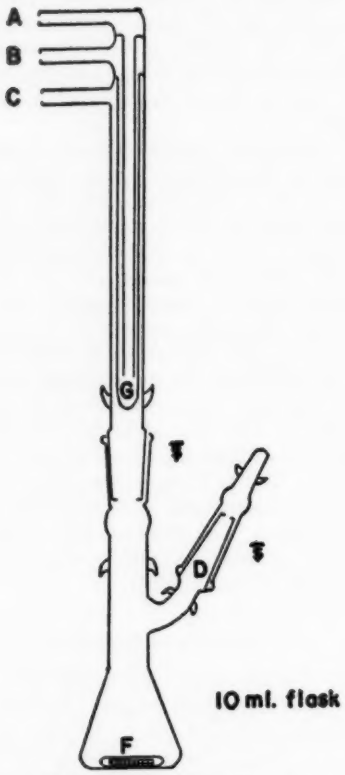

FIGURE 3. LEAD TETRAMETHYL REACTION APPARATUS

Lead tetramethyl was synthesized in a reaction apparatus similar to that shown in Figure 3. The simple water-cooled reflux condenser AGB was connected by standard taper ground glass joints to a 10 ml erlenmeyer flask provided with a side arm D for inserting reagents and removing reaction products. Up to 200 mg of dry lead chloride or lead iodide were placed in the flask and refluxed for 4 hours at about 45°C with an excess (5 ml) of 0.5 mole-per-liter Grignard reagent. Stirring of the components was accomplished by means of a magnetic stirrer F. The reflux condenser AGB was furnished with a lead-in C through which dry, oxygen-free nitrogen at a small positive pressure could be supplied to the flask during the refluxing period. Reaction was stopped at the end of 4 hours by the cautious addition of water to the reaction vessel, and the resulting ether-water mixture was placed in a separatory funnel. The ether layer, containing the lead tetramethyl in solution, was then drawn off and dried by the addition of a small quantity of anhydrous calcium sulphate. A fairly complete separation of the ether and tetramethyl was effected by first fractionating most of the ether off in air at a temperature of 45–50°C. The sample tube containing the residual liquid was then attached to the mass spectrometer sample line, the sample frozen in liquid air, and the air removed from the tube by pumping. Several fractions of the final solution were discarded, depending on the concentration of the ether present, and the final tetramethyl-rich fraction was examined in the spectrometer. However, such a procedure involves the loss of a certain percentage of the tetramethyl, thereby restricting analysis to samples containing a minimum of 50 mg of lead chloride or lead iodide.

At the suggestion of Dr. G. F Wright of the Department of Chemistry, University of Toronto, the use of methyl Grignard reagent prepared with isoamyl ether is being investigated. The minimum quantity of $PbCl_2$ or PbI_2 necessary for satisfactory analysis has been reduced to 10 mg in this way. This is comparable to the amount of sample used by Nier (1938, p. 1571) who utilized solid PbI_2 as a source of ions.

Results

The isotopic constitutions of 96 radiogenic leads extracted from uranium-bearing samples taken from uranium deposits are listed in Table 1. In the same table ages are given from the ratio of radiogenic Pb^{207}/Pb^{206} for all samples which showed a low ordinary lead content. Chemical analyses for a number of the samples have been listed in Table 2. Lang and Robinson of the Geological Survey of Canada have described the geology and mineralogy of a number

of uranium deposits in the Canadian Shield from which a substantial part of the samples in Table 1 were taken (Collins, Lang, Robinson, and Farquhar, 1952).

Crystals of uraninite from pegmatite rocks are the most suitable of the uranium-bearing minerals for age determinations. Uraninite crystals are usually well preserved, and they are believed to have crystallized at about the same time as the host rock. The relation of the age of hydrothermal pitchblende deposits to the age of the rocks in which they occur is less certain. It is believed that in general pitchblendes were deposited with other metals during the closing stages of an orogeny. However, this hydrothermal mineralization process could easily be reversed at some subsequent time by the dissolution of the original pitchblendes and the redeposition of this material. If such were the case, the age found for the pitchblende would date the time of most recent deposition, and only the ages of the oldest deposits would set a useful younger limit to the age of the host rock.

Age Determination

In the following sections the age determinations are discussed according to the regions in which the corresponding deposits occur (Lang, 1952). An attempt is made to estimate the most probable age of the different regions from the results of Table 1 and from previous results taken from the literature.

Eldorado Mine, Great Bear Lake, Northwest Territories

Seven samples of pitchblende (Nos. 1 to 7, Table 1) submitted by several collectors were analyzed. The ages are lised in Table 3. Samples 1 and 2, taken from underground and surface, are in reasonable agreement. Samples 6 and 7 have been rejected because of the large errors arising from common lead contamination. The average of the ages for samples 1 to 5, combined with Nier's value of 1420 m.y. (Nier 1939) is 1400 m.y., which we estimate to be probably correct to within 50 m.y. Chemical ages from the ratio of Pb^{206}/U^{238} which have appeared in the literature have been somewhat lower, about 1330 m.y., probably because of loss of Pb in recent geological time.

The time relation of the country rock has been discussed in a recent paper.

> "Rocks of the Echo Bay group are intruded by granodiorite, granite, early diabase and later diabases being the youngest rocks known in the vicinity of the mine. Early diabase dykes are known to be earlier than the pitchblende veins, and tongues of later diabase intrude the veins. The pitchblende mineralization occurred, therefore, during the interval between the intrusion of the two types of diabase." (Collins, Lang, Robinson, and Farquhar, 1952, p. 28).

We can only conclude that the country rocks about Eldorado Mine are older than 1400 m.y.

Hottah Lake Region, Northwest Territories

The Hottah Lake region is close to the western edge of the Canadian Shield, about 80 miles south of the Eldorado Mine on Great Bear Lake. Beaverlodge Lake, Northwest Territories, is immediately south of Hottah Lake. Geological evidence shows that the pitchblendes in this area are younger than the youngest Precambrian rocks (Collins, Lang, Robinson, and Farquhar, 1952, p. 29). Our single age for the Isabella property of 580 ± 60 m.y. is higher than most chemical determinations such as that of Kidd (1936, p. 25) which averaged 350 m.y. for samples from the Tatee claim, Beaverlodge Lake. Nier (1939, p. 159) reported a chemical age of 333 m.y. and an isotopic age from the ratio of Pb^{207}/Pb^{206} for Beaverlodge Lake pitchblende of 460 m.y. From these ages it would appear that the pitchblendes in this area are much younger than those at the Eldorado Mine, Great Bear Lake, although older deposits that have not been investigated may exist. In any case the pitchblendes are geologically younger than the country rock, but how much younger we cannot say.

Lac La Ronge Region, Saskatchewan

The Lac La Ronge region is in the Canadian Shield in central Saskatchewan. One sample from these recently reported deposits was sent to us by J. B. Mawdsley, of the University of Saskatchewan, who classed it as uraninite so that it probably is from a pegmatite. It is

TABLE 1.—RELATIVE ABUNDANCES OF THE ISOTOPES OF 96 SAMPLES OF RADIOGENIC LEAD

No.	Location and property	Source	Isotopic constitution (%)				Radiogenic constitution (%)			Ratio radiogenic Pb^{207}/Pb^{206} %	Age ($\times 10^6$ yr)
			Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}	Pb^{204}	Pb^{207}	Pb^{208}		
	Great Bear Lake (pitchblende)										
1	Eldorado (surface)	(1)	0.056 ±0.01	89.47	8.69	1.78	88.67	7.92	..	8.93 ± 0.25	1430 ± 40
2	Eldorado (underground)	(1)	0.021 ±0.01	90.63	8.29	1.10	90.30	7.97	..	8.83 ± 0.30	1410 ± 60
3	Eldorado	(2)	0.07 ±0.03	88.90	8.43	2.61	87.80	7.37	..	8.39 ± 0.20	1330 ± 40
4	Eldorado	(3)	0.07 ±0.015	89.57	8.44	1.90	88.71	7.62	..	8.59 ± 0.25	1350 ± 50
5	Eldorado	(4)	.....	90.30	8.44	1.26	90.02	8.17	..	9.08 ± 0.35	1460 ± 70
6	Eldorado	(5)	0.31 ±0.03	75.67	11.25	12.80	70.72	6.50	..	9.19 ± 0.70	1480 ± 130
7	Eldorado	(5)	0.16 ±0.03	86.21	8.85	4.78	83.66	6.40	..	7.65 ± 0.60	1130 ± 130
	Hottah Lake (pitchblende)										
8	Isabella	(1)	0.01	93.85	5.63	0.53	93.73	5.52	..	5.88 ± 0.15	580 ± 60
9	Cormac	(1)	0.33 ±0.015	69.66	9.54	20.50	.....	..	..	.....	.....
	Marian River										
10	Giauque	(1)	0.55 ±0.01	64.54	11.89	23.03	.....	..	..	.....	.....
	Lac La Ronge										
11	Lee Lake (uraninite)	(6)	0.035 ±0.015	87.06	9.63	3.34	86.49	9.09	2.10	10.51 ± 0.20	1740 ± 50
	Charlebois Lake										
12	Charlebois Lake	(1)	0.044 ±0.004	85.66	9.83	4.47	84.98	9.16	2.94	10.78 ± 0.06	1780 ± 50
	Stark Lake Region										

	Stark Lake Region										
13	Rex (uraninite)	(1)	0.073 ±0.015	86.83	10.67	2.44	85.68	9.57	..	11.17 ± 0.30	1850 ± 40
14	Rag (pitchblende)	(1)	0.01	90.06	9.46	0.49	89.95	9.35	..	10.39 ± 0.20	1700 ± 30
	Goldfields (pitchblende)										
15	Lake Athabasca	(3)	0.05	88.45	9.64	1.92	88.01	9.22	..	10.48 ± 0.42	1730 ± 100
16	Fish Hook Bay (Hacker vein)	(1)	0.03 ±0.015	88.18	10.35	1.46	87.71	9.90	..	11.29 ± 0.30	1850 ± 50
17	Strike Group (Ace Lake)	(7)	0.23 ±0.015	80.18	11.76	8.84	76.50	8.23	..	10.76 ± 0.25	1780 ± 40
18	Ace Mine	(1)	0.00 ±0.015	89.69	9.96	0.37	89.62	9.87	..	11.02 ± 0.20	1820 ± 40
19	Nicholson No. 4	(1)	0.00 ±0.015	89.49	9.88	0.66	89.34	9.74	..	10.89 ± 0.20	1800 ± 40
20	Nicholson No. 4	(8)	0.04 ±0.02	90.82	7.24	1.90	90.19	6.64	..	7.36 ± 0.40	1050 ± 90
21	Nicholson No. 4	(7)	0.03 ±0.02	90.39	7.51	2.10	89.92	7.06	..	7.85 ± 0.35	1180 ± 80
22	Nicholson No. 2	(1)	.....	92.46	7.25	0.17	92.42	7.22	..	7.81 ± 0.05	1160 ± 20
23	Martin Lake	(8)	.....	90.24	9.27	0.51	90.13	9.16	..	10.16 ± 0.11	1670 ± 30
24	Martin Lake	(8)	.....	90.04	9.21	0.78	89.87	9.04	..	10.06 ± 0.17	1660 ± 40
25	Martin Lake	(8)	.....	90.54	9.21	0.26	90.48	9.16	..	10.12 ± 0.06	1660 ± 20
26	Martin Lake	(8)	.....	90.79	9.18	0.28	90.76	8.62	..	10.04 ± 0.07	1650 ± 20
27	Martin Lake	(8)	.....	90.56	9.01	0.43	90.47	8.92	..	9.86 ± 0.10	1620 ± 30
28	Martin Lake	(1)	0.14 ±0.03	87.02	9.78	3.03	85.65	8.47	..	9.89 ± 0.20	1620 ± 40
29	Martin Lake	(8)	trace	89.84	8.80	1.41	89.51	8.50	..	9.49 ± 0.31	1610 ± 50
30	Martin Lake	(5)	0.03 ±0.02	89.48	9.06	1.45	89.01	8.61	..	9.67 ± 0.31	1580 ± 60
31	Martin Lake	(8)	.....	90.63	8.85	0.54	90.51	8.74	..	9.65 ± 0.11	1570 ± 30
32	Martin Lake	(8)	.....	90.79	8.63	0.59	90.66	8.50	..	9.37 ± 0.15	1530 ± 40
33	Martin Lake	(8)	.....	91.29	8.16	0.58	91.16	8.04	..	8.82 ± 0.12	1410 ± 30
34	Martin Lake	(5)	.....	92.33	7.14	0.54	92.21	7.03	..	7.62 ± 0.15	1110 ± 40
35	Eagle	(1)	.....	89.99	9.41	0.63	89.85	9.28	..	10.33 ± 0.15	1700 ± 30
36	Eagle	(8)	.....	90.37	9.10	0.55	90.25	8.98	..	9.95 ± 0.12	1630 ± 30

TABLE 1.—*Continued*

No.	Location and property	Source	Isotopic constitution (%)				Radiogenic constitution (%)			Ratio radiogenic Pb^{207}/Pb^{206} %	Age ($\times 10^6$ yr)
			Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}	Pb^{206}	Pb^{207}	Pb^{208}		
	Goldfields—*Continued* (pitchblende)										
37	Eagle	(8)	0.10 ±0.015	87.64	9.66	2.59	86.47	8.54	..	9.88 ± 0.20	1620 ± 50
38	Eagle	(1)	—	91.30	8.25	0.45	91.20	8.16	..	8.95 ± 0.10	1430 ± 40
39	50-DD-22	(9)	0.16 ±0.04	81.54	10.28	8.05	79.02	7.87	..	9.96 ± 0.67	1630 ± 130
40	Rix	(1)	0.165 ±0.015	83.23	10.30	6.30	80.63	7.82	..	9.70 ± 0.26	1590 ± 50
41	Rix	(7)	0.064 ±0.015	89.16	8.30	2.47	88.16	7.34	..	8.38 ± 0.18	1310 ± 50
42	Rix	(7)	0.043 ±0.010	90.92	7.77	1.26	90.35	7.22	..	7.99 ± 0.18	1210 ± 50
43	Cinch Lake	(7)	—	92.48	7.14	0.40	92.39	7.06	..	7.64 ± 0.10	1120 ± 40
44	Cinch Lake	(7)	0.01	92.69	6.98	0.34	92.62	6.91	..	7.46 ± 0.08	1070 ± 40
45	Cinch Lake	(7)	0.015 ±0.01	92.20	6.92	0.88	92.00	6.73	..	7.31 ± 0.20	1030 ± 50
46	49-CC-11	(7)	—	92.69	7.19	0.11	92.67	7.17	..	7.73 ± 0.03	1140 ± 20
47	Mic Lake	(8)	0.06 ±0.03	88.86	7.93	3.13	87.92	7.03	..	8.00 ± 0.46	1210 ± 120
48	Mic Lake	(8)	0.04 ±0.01	90.41	7.59	1.98	89.78	6.99	..	7.78 ± 0.16	1160 ± 40
49	Gully, Beth Zone	(8)	—	92.65	6.70	0.67	92.50	6.56	..	7.09 ± 0.15	970 ± 50
50	Tam Lake	(8)	—	92.89	6.61	0.52	92.78	6.50	..	7.01 ± 0.10	945 ± 40
51	YY Concession	(1)	—	93.14	6.55	0.33	93.07	6.48	..	6.98 ± 0.07	940 ± 30
52	Gil Group	(1)	0.01	93.29	6.52	0.19	93.25	6.48	..	6.95 ± 0.04	930 ± 20
53	50-AA-14	(9)	—	92.97	6.53	0.53	92.85	6.42	..	6.91 ± 0.12	920 ± 50
54	ABC Group	(1)	—	93.09	6.45	0.49	92.98	6.35	..	6.83 ± 0.12	920 ± 50
55	ABC Group	(1)	0.435 ±0.020	71.70	11.35	16.54	.....	..	..	.....	.....
56	Donaldson	(8)	.....	92.95	6.36	0.71	92.79	6.21	..	6.69 ± 0.16	850 ± 60
57	50-CC-61	(7)	0.10 ±0.005	88.72	6.89	4.28	87.15	5.38	..	6.17 ± 0.08	680 ± 50

57	50-CC-61	(7)	0.10 ±0.005	88.72	6.89	4.28	87.15	5.38	..	6.17 ± 0.08	680 ± 50
58	Bolger	(1)	0.01	94.43	5.20	0.38	94.35	5.12	..	5.43 ± 0.09	400 ± 50
59	Pitch Group	(1)	0.05 ±0.02	91.78	5.86	2.34	91.04	5.15	..	5.66 ± 0.31	490 ± 130
60	Pitch Group Hottah Lake	(1)	0.283 ±0.013	76.39	9.08	14.27	.....	..	..	.....	.....
61	Ace Creek Zone	(8)	0.69 ±0.02	60.52	14.98	23.75	.....	..	..	.....	.....
62	Ace Creek Zone (galena)	(1)	1.01 ±0.02	43.98	18.88	36.11	.....	..	..	.....	.....
63	Ace Creek Zone	(8)	0.62 ±0.03	62.99	14.12	22.29	.....	..	..	.....	.....
64	Ace Creek Zone	(8)	0.74 ±0.02	53.74	16.27	29.26	.....	..	..	.....	.....
65	Cross Point	(1)	0.18 ±0.06	88.14	7.47	3.76	.....	..	..	.....	.....
66	FF #4	(1)	0.410 ±0.010	75.07	9.70	14.81	.....	..	..	.....	.....
	Black Lake (pitchblende)										
67	Black Lake	(8)	.....	91.81	7.59	0.62	91.67	7.46	..	8.14 ± 0.14	1250 ± 50
68	Nisto Mine	(8)	.....	92.27	7.48	0.26	92.21	7.43	..	8.05 ± 0.10	1230 ± 40
	Sault Ste. Marie (pitchblende)										
69	Theano Pt.	(12)	0.18 ±0.03	84.40	8.99	6.49	81.73	6.43	..	7.87 ± 0.50	1190 ± 120
70	Theano Pt.	(10)	0.096 ±0.015	87.63	8.18	4.13	86.12	6.73	..	7.81 ± 0.25	1190 ± 40
71	Theano Pt.	(10)	0.052 ±0.02	91.83	5.74	2.39	91.01	4.96	..	5.45 ± 0.31	400 ± 130
72	Ranwick	(1)	0.10 ±0.015	87.08	8.30	4.53	85.44	6.73	..	7.88 ± 0.23	1180 ± 60
73	LaBine-McCarthy	(1)	0.19 ±0.015	82.52	9.01	8.31	79.49	6.10	..	7.67 ± 0.26	1130 ± 70
74	Camray	(11)	0.20 ±0.03	84.42	8.72	6.65	81.43	5.86	..	7.20 ± 0.50	1000 ± 150

TABLE 1.—*Continued*

No.	Location and property	Source	Isotopic constitution (%)				Radiogenic constitution (%)			Ratio radiogenic Pb^{207}/Pb^{206} %	Age ($\times 10^6$ yr)
			Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}	Pb^{206}	Pb^{207}	Pb^{208}		
	Grenville Province										
75	Wilberforce (uraninite)	(8)	0.01	89.53	6.72	3.84	89.53	6.72	3.84	7.51 ± 0.20	1090 ± 50
76	Wilberforce (uraninite)	(2)	0.12 ±0.03	82.34	7.91	9.64	80.45	6.10	5.46	7.58 ± 0.50	1100 ± 130
77	Wilberforce (pit No. 4) (uraninite)	(12)	0.006	89.67	6.56	3.76	89.67	6.56	3.76	7.31 ± 0.03	1032 ± 10
78	Wilberforce (pit No. 4) (uraninite)	(12)	0.00 ±0.01	89.43	6.60	3.98	89.35	6.53	3.80	7.38 ± 0.07	1040 ± 15
79	Calabogie (Euxenite or samarskite)	(5)	0.03	88.88	6.66	4.50	88.64	6.43	3.98	7.26 ± 0.24	1010 ± 70
80	Madawaska (fergusonite)	(13)	0.01 ±0.007	90.71	6.54	2.77	90.54	6.37	2.39	7.04 ± 0.15	960 ± 50
	Appalachian Province										
81	Ruggles Mine N. H.	(2)	0.09 ±0.03	89.63	6.37	3.99	88.03	4.97	..	5.65 ± 0.50	455 ± 160
82	Mitchell Co. N. C.	(2)	0.007 ±0.007	94.48	5.14	0.40	94.35	5.03	..	5.33 ± 0.09	355 ± 40
	South Africa										
83	Katanga, Belgian Congo (pitchblende)	(3)	.....	94.21	5.66	0.13	94.18	5.63	..	5.98 ± 0.03	612 ± 15
84	Kalongwe, Belgian Congo (pitchblende)	(14)	0.035	93.90	5.76	0.32	93.76	5.62	..	5.99 ± 0.04	615 ± 20
85	Shinkolobwe Bel. Congo (pitchblende)	(14)	0.02 ±0.01	93.68	5.82	0.51	93.45	5.60	..	5.99 ± 0.06	615 ± 20
86	Shinkolobwe Bel. Congo (pitchblende)	(14)	0.024 ±0.015	94.09	5.79	0.11	94.04	5.75	..	6.10 ± 0.02	655 ± 20
87	Shinkolobwe Bel. Congo (pitchblende)	(14)	0.054 ±0.015	92.96	6.02	0.97	92.52	5.60	..	6.05 ± 0.10	637 ± 50
88	Shinkolobwe Bel. Congo (pitchblende)	(14)	0.015 ±.008	93.94	5.79	0.25	93.83	5.68	..	6.05 ± 0.03	637 ± 20
89	Witwatersrand (uraninite)	(15)	0.050 ±0.008	84.78	11.57	3.61	81.83	10.37	1.60	12.67 ± 0.50	2070 ± 100

89	Witwatersrand (uraninite)	(15)	0.050 ±0.008	84.78	11.57	3.61	81.83	10.37	1.60	12.67 ± 0.50	2070 ± 100
90	Witwatersrand (galena)	(15)	0.805 ±0.010	47.45	19.40	32.35	.....	..	..	.....	.....
	Australia										
91	Hart's Range (samarskite)	(12)	0.34 ±0.07	75.51	9.82	14.36	.....	..	..	.....	.....
92	Radium Hill (davidite)	(12)	0.21 ±0.015	78.70	10.34	10.78	75.36	7.13	..	9.46 ± 0.40	1540 ± 100
	England										
93	Cornwall (uraninite)	(2)	1.13 ±0.015	35.67	18.75	44.41	.....	..	..	.....	.....
	Bohemia										
94	Joachimsthal (pitchblende)	(2)	0.85 ±0.02	50.45	15.56	33.15	.....	..	..	.....	.....
95	Joachimsthal (pitchblende)	(3)	0.597 ±0.015	63.54	12.19	22.65	.....	..	..	.....	.....
	United States										
96	Colorado	(16)	0.012 ±0.006	90.72	8.56	0.72	90.53	8.38	..	9.26 ± 0.09	1500 ± 30
	Spain										
97	Sierra Albarrana, Cordova. (pitchblende)	(16)	0.13 ±0.02	87.99	6.51	5.37	85.99	4.60	..	5.35 ± 0.37	360 ± 150

Sources of samples

1. A. H. Lang, S. C. Robinson, and H. V. Ellsworth, Geological Survey of Canada, Ottawa, Ontario
2. V. B. Meen, Royal Ontario Museum, Toronto, Ontario
3. H. G. Thode, McMaster University, Hamilton, Ontario
4. J. Walters, Geophysics Laboratory, University of Toronto
5. W. F. James and B. S. W. Buffam, Consulting Geologists, Toronto, Ontario
6. J. B. Mawdsley, Geology, University of Saskatchewan, Saskatoon, Saskatchewan
7. G. Harper, Geological Sciences, University of Toronto
8. F. Clifton, Geophysics, University of Toronto
9. W. H. Gross, Geological Sciences, University of Toronto
10. E. W. Nuffield, Geological Sciences, University of Toronto
11. Camray Mines, Ltd., Ontario
12. J. T. Wilson and C. B. Collins, Geophysics, University of Toronto
13. D. F. Hewitt, Ontario Department of Mines
14. L. Cahen, Section de Geologie, Musee du Conge Belge
15. C. F. Davidson, Geological Survey of Great Britain, London, England
16. J. P. Marble, National Research Council, Washington, D. C., U. S. A.

hoped that further samples will be available from this locality together with sufficient information to establish the relation of the uranium mineralization to the time of emplacement of the country rock.

Charlebois Lake, Saskatchewan

A single sample of uranium-bearing material from Charlebois Lake, submitted by S. C. Robinson of the Geological Survey of Canada,

TABLE 2.—CHEMICAL AND ISOTOPIC AGES OF URANIUM MINERALS

Sample No.	Locality	U	Th	Pb	Ages in 10^6 yr.			
					Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{208}/Th^{232}	Pb^{207}/Pb^{206}
16	Pitchblende, Fish Hook Bay, Goldfields, Sask.	6.49	....	1.63	1485	1648	..	1850 ± 50
30	Pitchblende, Martin Lake, Goldfields, Sask.	4.88	0.0009	0.30	400	630	..	1580 ± 60
51	Pitchblende, YY Concession, Goldfields, Sask.	0.916	0.0018	0.25	190	260	..	940 ± 30
52	Pitchblende, Gil Group, Goldfields, Sask.	8.21	0.0097	1.02	822	850	..	930 ± 20
53	Pitchblende, 50-AA-14, Goldfields, Sask.	32.02	0.0009	2.83	592	664	..	920 ± 50
58	Pitchblende, Bolger, Goldfields, Sask.	19.20	0.0026	1.24	444	437	..	400 ± 50
77	Uraninite, Pit #4, Wilberforce, Ont.	60.09	7.93	11.18	1150	1110	1130	1032 ± 10
79	Euxenite or Samarskite, Calabogie, Ont.	4.16	1.11	0.42	642	732	337	1010 ± 70
89	Uraninite, Witwatersrand, South Africa.	61.32		14.84	1340	1650	..	2070 ± 50

Chemical analyses of samples Nos. 30 to 79 were carried out by the National Laboratories, Teddington, England, through the courtesy of F. H. Burstall. Sample No. 16 was analyzed by the Geological Survey of Canada, through the courtesy of H. V. Ellsworth. C. F. Davidson provided the data for No. 89.

For a single sample from Lee Lake, Lac La Ronge, sample No. 11, Table 1, an age of 1740 ± 50 m.y. was found. The analysis was satisfactory in that there was very little contaminating ordinary lead present, but it is desirable to check this age by analysis of other samples. The significance of this age determination and of those immediately following will be discussed together in the section on the Athabasca or Churchill Province.

was analyzed and found to have an age of 1780 ± 50 m.y. We have no more information about this sample.

Stark Lake Region, Northwest Territories

Stark Lake is immediately south of the east arm of Great Slave Lake, about 130 miles east of Yellowknife. Two samples, one of pitchblende from the Rag property (No. 14, Table 1)

and one of uraninite from the Rex property (No. 13, Table 1), were analyzed. Evidence presented by Lang (Collins, Lang, Robinson, and Farquhar, 1952, p. 30) shows that the Rex uraninite occurs in pegmatites believed to have been emplaced shortly after the associated intrusive rocks. The age of 1850 ± 40 m.y. for the Rex property uraninite may therefore be considered a geological age closely dating the time of crystallization of these pegmatites. Analysis of the Rag property pitchblende gave an age of 1700 ± 30 m.y. which sets a younger limit on the age of the rocks at this property, which from geological evidence were laid down after the Rex property pegmatites.

TABLE 3.—AGES OF GREAT BEAR LAKE PITCHBLENDES

SAMPLE NO.	Age in 10^6 yr. from ratio of Pb^{207}/Pb^{206}
1 (Underground)	1430 ± 40
2 (Surface)	1410 ± 60
3	1330 ± 40
4	1350 ± 50
5	1460 ± 70
6	1480 ± 130
7	1130 ± 130
(Nier, 1939)	1420

Goldfields and Black Lake Region, Saskatchewan

The Goldfields region immediately north of Lake Athabasca is the most important uranium-bearing district discovered in Canada since the discoveries at Great Bear Lake. A very large number of pitchblende occurrences have now been found in the Goldfields region (Lang, 1951, p. 65), many of which are being actively explored by mining companies, and much geological and mineralogical work is being done. Because of the interest in this region, more age determinations have been made on samples from here than from any other part of the Canadian Shield.

A major part of the ages, without isotopic analyses, for uranium-bearing samples from the Goldfields region, which appear in Table 1, have already been reported, together with a description of the geology and mineralogy of the area (Collins, Lang, Robinson, and Farquhar, 1952, p. 21). Two plots of these age values have been made: Figure 4 shows ages from the Martin Lake pitchblendes; Figure 5 includes all the ages for samples from the Goldfields region, Black Lake, and Stark Lake immediately south of the east arm of Great Slave Lake.

Martin Lake, Saskatchewan (Fig. 4)

Twelve samples were analyzed from this deposit in the Goldfield area in an attempt to find out whether reproducible age values could be obtained. Most of the ages were close to 1630 m.y.; but two samples (33 and 34, Table 1) gave lower values.

Athabasca or Churchill Province (Fig. 5)

The oldest pitchblendes in the Goldfields region are up to 1850 m.y. old. This age agrees with the 1850 m.y. found for uraninite from the Rex pegmatite at Stark Lake. The uraninites from the Lac La Ronge and Charlebois Lake areas, which are also probably from pegmatites, are only slightly younger. This is probably the age of the major acid intrusive of the region and indicates that this area from Great Slave Lake on the north to at least Lac La Ronge on the south is probably one orogenic belt or geological province. Wilson (1949a, p. 179) and Gill (1949, p. 64) have suggested from geological evidence that this area is a single orogenic belt. The Martin Lake deposit which is well dated at 1630 m.y. occurs in almost flat-lying and relatively unmetamorphosed sandstone of Lake Athabasca or Proterozoic type. This shows that mountain building was completed in this region before that date. It is concluded that the Athabasca province was in process of being actively built into mountains 1850 m.y. ago and that the orogeny was over before 1630 m.y. ago. To explain the ages found for pitchblendes in the Goldfields area at Beaverlodge Lake, Saskatchewan, it was assumed that the oldest samples in the 1850 m.y. group were probably deposited during the closing stages of the orogeny during which the country rock was metamorphosed into its present form (Wilson, 1949a, p. 179). Certainly the Rex property uraninite from Stark Lake could be so interpreted, and one of

the Goldfields pitchblendes from Hacker Vein occurred in a high-temperature pegmatitic deposit which was probably emplaced during the closing stages of an orogeny. All the younger ages (with the possible exception of Martin Lake which is in geologically younger structure) were believed to date more recent deposits. The pitchblende for these younger deposits is believed to have come from the dissolution and redeposition of the primary pitchblende deposits. The evidence supports this explanation:

(1) Galena from Ace Creek Zone contains about 30 per cent radiogenic lead, and galena from the Box mine about 7 per cent. This could be due either to diffusion of radon or to solution and redeposition of pitchblende and galena.

"If the first hypothesis [radon loss] is accepted, diffusion on a large scale is indicated and, furthermore, this diffusion must have penetrated to considerable distances, (at least tens of feet) from the parent pitchblende. Moreover, it is difficult to understand how diffusion alone could account for a content of 30 per cent radiogenic lead in solid galena.

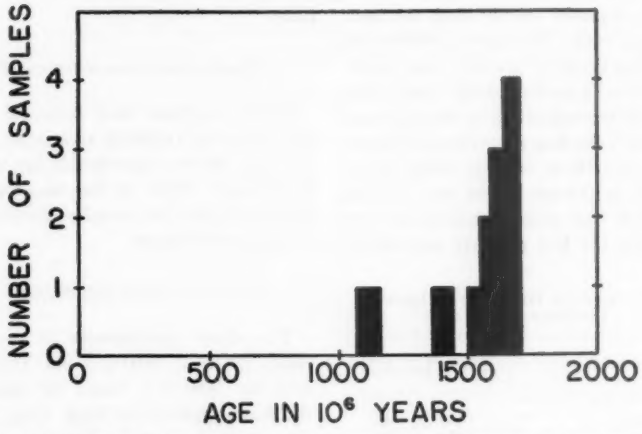

FIGURE 4. AGES OF PITCHBLENDES FROM MARTIN LAKE, GOLDFIELDS, SASKATCHEWAN

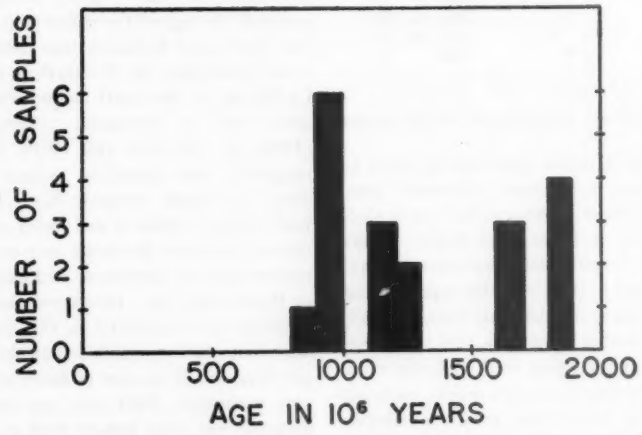

FIGURE 5. AGES OF PITCHBLENDES AND URANINITES FROM THE CHURCHILL GEOLOGICAL PROVINCE

Since the radon (Rn^{222}) produced by the decay of U^{238} to Pb^{206} has a half life of 3.8 days compared with the radon (Rn^{219}) generated in the U^{235} decay to Pb^{207} which has a half life of 3.9 seconds, almost all the loss would be Rn^{222}. Then Pb^{206} would be low in the pitchblende and high in the galena, and the ages determined from the ratio of radiogenic Pb^{207}/Pb^{206} from the pitchblende would be high. .... There is no evidence from the age determinations that such a process took place.

"The second hypothesis [solution and redeposition of pitchblende] seems to be more in accord with the known facts. There is considerable evidence indicating that not only is there more than one generation of pitchblende but also that at least some of the deposits, notably the Ace, have been reopened and reworked by hydrothermal solutions subsequent to those from which the original pitchblende was deposited. The evidence does suggest that later solutions might redissolve and reprecipitate the early pitchblende" (Collins, Lang, Robinson, and Farquhar, 1952 p. 36).

(2) Mineralogical studies showed that several deposits had been reopened and reworked by hydrothermal solutions subsequent to those from which the original pitchblende was deposited.

(3) Samples of pitchblende from the Nicholson No. 4 Mine and from the Martin Lake property showed old and young pitchblendes associated with one deposit.

Sault Ste. Marie Region, Ontario

Samples 69 to 74 (Table 1) were taken from pitchblende deposits associated with the contact of diabase dike intrusions in the region of Theano Point and the mouth of the Montreal River north of Sault Ste. Marie. Except for one young sample, which was probably reworked material, the most probable age is about 1200 ± 50 m.y. Since the pitchblende was associated with the contact of diabase dikes which intruded the older Keewatin rocks, the age of 1200 ± 50 m.y. sets a younger limit on the time of the diabase intrusion. The Keewatin rocks are believed to be a good deal older.

Grenville Province, Ontario and Quebec

Samples 75 to 78 (Table 1) came from the Wilberforce uraninite deposits. Samples 77 and 78 were well-preserved crystals and are the most satisfactory of those reported. Their ages agree well with the value of 1030 m.y. which had already been established by Ellsworth (1932, p. 105), Nier (1939, p. 159), and other investigators.

Since another age determination in the Grenville, by Nier (1939, p. 159) on Besner uraninite, gave a value of 825 m.y., the best present estimate is that the Grenville orogeny took place over a period from 800 to 1100 m.y. ago. Age determinations from samarskite and fergusonite minerals from Calabogie and Madawaska (samples 79 and 80) also fall in this same age range. Individual minerals in a particular locality may of course be dated much more precisely. The age of the Wilberforce uraninite, for example, is believed to be good to within 1 to 2 per cent, and this may well be one of the most accurately dated localities yet investigated.

Appalachian Region

The Appalachian region has long been recognized as an orogenic belt which was formed during the period from 200 to 600 m.y. ago (Wilson, 1949b, p. 231). The time of formation was estimated from the ages of uranium minerals and from paleontological evidence.

One sample from Mitchell County, North Carolina, listed in Table 1 was found to have an age of 355 ± 40 m.y. Another from Ruggles mine, New Hampshire, had a rather large ordinary lead contamination, but has been estimated to be 455 ± 160 m.y. old.

South Africa

Holmes (1949) has summarized age determinations from South Africa in an excellent paper. A subsequent paper by Ahrens and Macgregor (1951, p. 64) gives strontium ages for nine lepidolite specimens from Southern Rhodesia. To date we have only checked Nier's value for Katanga and added a determination from Witwatersrand.

Katanga, Belgian Congo

Samples 83 to 88 (Table 1) from Shinkolobwe and Kalongwe pitchblende deposits have ages from 612 to 655 m.y. This age range agrees well with the ages of from 610 to 655 m.y. found by Nier (1939 p. 159) for the Kalongwe deposits.

Apparently the two deposits were formed about the same time, some 630 m.y. ago.

Witwatersrand, Transvaal, South Africa

Samples 89 and 90 (Table 1) were sent to us through the kindness of Dr. C. F. Davidson of the Geological Survey of Great Britain. The Rand uraninite (sample 89) had been laboriously prepared from low-grade ore which was reported to contain no more than 100 or 200 grams per ton. The final concentrate by ratiometric assay was about 75 per cent equivalent U_3O_8. As a check on the galena present in the original material, Davidson had a galena concentrate made which assayed only 0.11 per cent U_3O_8. The isotopic constitution of the galena is reported in Table 1 (sample 90).

In spite of the high radiogenic lead content of the Rand galena, so little ordinary lead was present with the radiogenic lead from the uraninite that the correction for ordinary lead is not important. Therefore it makes little difference whether the contaminating lead is assumed to have the isotopic constitution of the Rand galena or of common lead such as reported by Nier, Thompson, and Murphey (1941, p. 115). However the mineral has been altered, as shown by a comparison of the ages calculated from the chemical (From Dr. Davidson, In press) and isotopic analyses, from the ratios of

Pb^{207}/Pb^{206}—2070 m.y.
Pb^{206}/U^{238}—1340 m.y.
Pb^{207}/U^{235}—1649 m.y.

We believe the isotopic age of 2070 m.y. to be closest to the true age, although the age of the deposits will be in doubt until more data have been obtained.

Of the remaining age determinations, only two will be considered in detail. Sample 92 from Radium Hill, N.S.W., Australia, has a fairly high ordinary lead content, but any error arising from this cause is not likely to be of great importance for a sample as old as this one. The age obtained for it was 1510 ± 100 m.y. Nier, Thompson, and Murphey (1941, p. 113) have reported a value of 1190 ± 400 m.y. for the age of a monazite sample from Mt. Isa Mine, Queensland, Australia.

Sample 96, from Colorado, was found to have an age of 1500 ± 30 m.y. This material was sent to us by Dr. J. P. Marble and was prepared by Dr. O. B. Muench.

Sequences of Orogenic Belts in the Canadian Shield

Gill (1949), Wilson (1949b), and others proposed that the Canadian Shield may be divided into a series of orogenic belts or geological provinces. The orogenic belts are distinguished by common rock types, uniformity of direction of foliation, and similarity of age determinations. The definition of boundaries is based on structural evidence. Figure 7 shows a revision of Wilson's map incorporating the most recent data.

Consideration of the Ages of Altered Minerals

Three independent calculations of the age of a mineral containing uranium and thorium are possible, based on the ratios Pb^{208}/Th^{232}, Pb^{206}/U^{238}, and Pb^{207}/Pb^{206}. When the three ages do not agree, it must be assumed that one or more of lead, uranium, and thorium have been lost from the mineral since its formation. Nier (1939) and Nier, Thompson, and Murphey (1941) found that the three ages usually did not agree, but that ages from the Pb^{207}/Pb^{206} ratio were consistent, while ages calculated from the other ratios varied greatly, even for samples from the same deposit. For seven samples of Katanga pitchblende he reported ages from the Pb^{207}/Pb^{206} ratio of from 610 to 655 m.y., while ages from the ratio Pb^{206}/U^{238} ranged from 580 to 1000 m.y. Nier pointed out that loss of uranium or lead would cause a smaller error in the Pb^{207}/Pb^{206} ages than those calculated from the other ratios. From his data Nier calculated a value of 7.13×10^8 years for the half life of U^{235}. Recent careful experimental measurements by Fleming, Cunningham, and Ghiorso (1951) on almost pure U^{235} gave 7.07×10^8 years for this same constant.

In the investigation, our ages from the ratio of radiogenic Pb^{207}/Pb^{206} agree with those of Nier for pitchblende from Great Bear Lake (samples 1 to 6, Table 1), Katanga (Samples

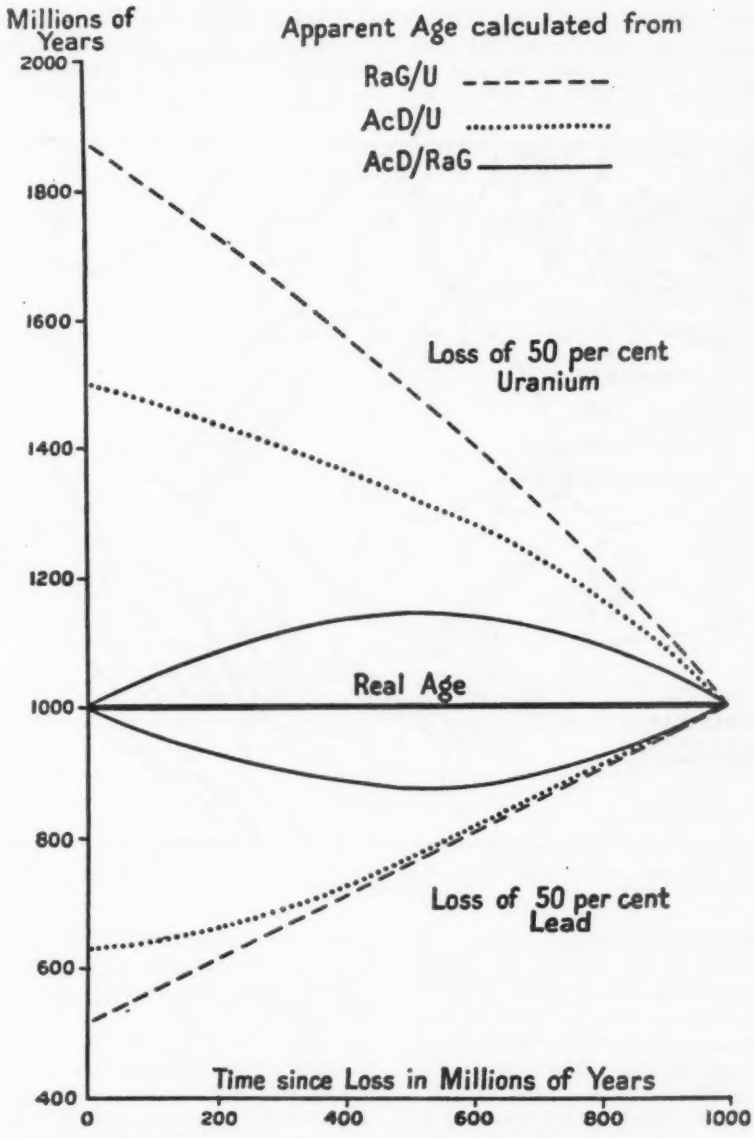

FIGURE 6. APPARENT AGE OF A ROCK WITH TRUE AGE 10^9 YEARS

83 to 88, Table 1), and for uraninite from Wilberforce (samples 77, 78, Table 1). Chemical ages from the ratio of Pb^{206}/U^{238} for samples from the same localities have generally been less consistent, but the assumed loss of Pb or U has always brought them into agreement with the much more consistent isotopic ages from the ratio of Pb^{207}/Pb^{206}.

The age of the Huron Claim pegmatite in Manitoba is of great interest to those con-

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cerned with radioactive age determinations. Several analyses of radioactive material from this pegmatite have been made, the most interesting being by Nier (1939, p. 159) and by

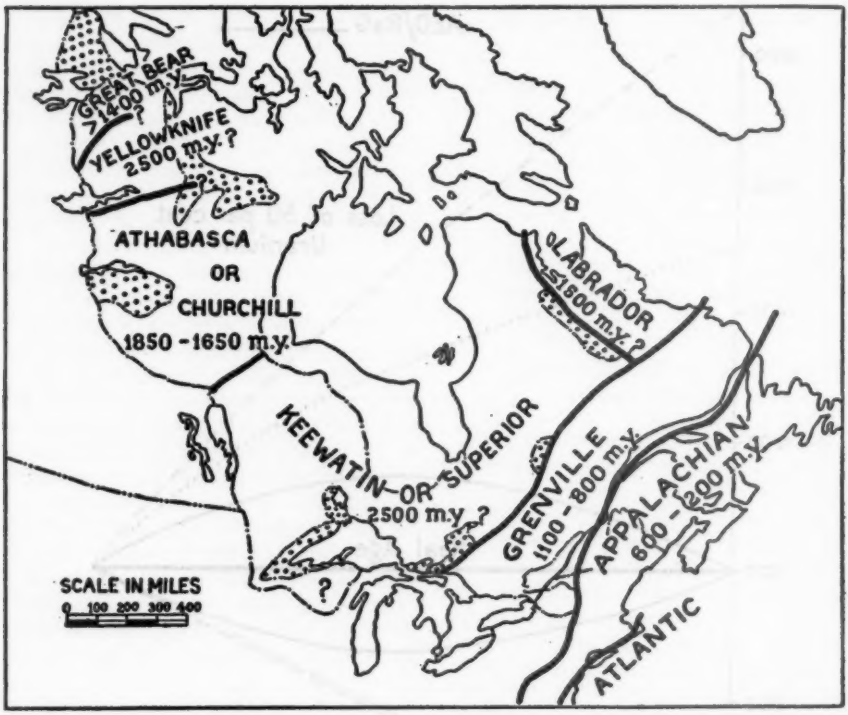

FIGURE 7. GEOLOGICAL PROVINCES OF THE CANADIAN SHIELD SHOWING DATES OF OROGENIES IN MILLIONS OF YEARS

Nier, Thompson, and Murphey (1941, p. 113). Holmes (1948, p. 182) discussed the analyses and reported a probable age based on a postulated loss of radon from the uranium series. However we do not believe that this interpretation is necessarily correct. Nier's data as interpreted by Holmes (1948, p. 189) appear in Tables 4 and 5. Holmes pointed out that the monazite results could be manipulated by the assumption of a 29 per cent loss of radon followed by a recent loss of 60 per cent of the Pb to agree with the 1985 m.y. age found for the uraninite sample in Table 4.

The isotopic ages for the uraninite sample of 2475 m.y. and for the monazite sample of 2590 m.y. obtained directly from Nier's data are in fair agreement. From analyses of radiogenic leads from other localities, it appears that the discrepancy between the consistent isotopic ages from the ratio of Pb^{207}/U^{206} and the inconsistent ages from the ratio of Pb^{206}/U^{238} can be explained by the recent loss of Pb or U through leaching (Fig. 4). Such is indeed the case, as is shown in Table 5. The postulated loss of 42.1 per cent of the lead for the uraninite sample and 22.1 per cent of the uranium in the monazite sample brings agreement with the isotopic ages from the ratio Pb^{207}/Pb^{208}.

Neither the connection based on the radon loss nor that based on lead or uranium loss is satisfactory. In Tables 4, 5, and 6 ages have been listed for the ratios of Pb^{207}/Pb^{206}, Pb^{208}/U^{238}, and Pb^{207}/U^{235}. This is a convenient way of examining the data, but in reality only two

TABLE 4.—URANINITE, HURON CLAIM, MANITOBA (Holmes, p. 189, 1948)
Chemical Analysis (Ellsworth)

Pb	U	Th	$\frac{Pb}{U+Th}$	$\frac{U}{U+Th}$	Apparent Age in m.y.
15.47	54.25	12.36	.239	.809	1680

Isotopic Analysis of Lead (Nier, 1939, No. 14)

Isotopic proportions	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
In total lead	.022	100.00	16.17	6.51
In original lead	.022	.32	.32	.75
In radiogenic lead	—	99.68	15.85	5.76
Per cent of radiogenic lead in uraninite	—	12.586	1.998	.726
	$\frac{Pb^{207}}{Pb^{206}}$	$\frac{Pb^{206}}{U}$	$\frac{Pb^{207}}{U}$	$\frac{Pb^{208}}{Th}$
Ratios	.1590	.2317	.0368	.0587
Apparent ages (m.y.)	2475	1564	1985	1273
Assuming leakage of radon equivalent to the loss of 31.4 per cent of the Pb^{206} now present, Pb^{206} becomes 16.514 and we get the following revised figures:				
Ratios	.1210	.3044	.0368	.0587
Apparent ages (m.y.)	1987	1987	1985	1273

TABLE 5.—MONAZITE, HURON CLAIM, MANITOBA (Holmes, 1948)
Chemical Analysis (Muench)

Pb	U	Th	$\frac{Pb}{U+Th}$	$\frac{U}{U+Th}$	Apparent Age in m.y.
1.524	.281	15.63	.958	.018	1955

Isotopic analysis of lead (Nier, Thompson, and Murphey, 1941, No. 28)

Isotopic proportions	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
In total lead	.011	11.6	2.11	100.00
In original lead	.011	.16	.16	.38
In radiogenic lead	—	11.44	1.95	99.62
Per cent of radiogenic lead in monazite		.153	.026	1.33
	$\frac{Pb^{207}}{Pb^{206}}$	$\frac{Pb^{206}}{U}$	$\frac{Pb^{207}}{U}$	$\frac{Pb^{208}}{Th}$
Lead ratios	.1705	.5445	.0929	.0854
Apparent ages	2590	3217	2839	1827

of the ratios are independent—the third is dependent on the others. Therefore when the age from one ratio value is selected as the most reliable and a second ratio value is adjusted to give the same age, the third age must always agree. Once this relationship is understood, it is easy to see why the adjusted age values agree to four significent figures, even though the experimental errors on the individual measurements are much larger. The adjustments of age

values for the postulated loss of radon, lead, or uranium from a mineral are therefore isotopic ratios of Pb^{207}/Pb^{206} at about 2500 m.y.

TABLE 6.—URANINITE AND MONAZITE, HURON CLAIM, MANITOBA

Sample	Ages in 10^6 yr.			
	Pb^{207}/Pb^{206}	Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{208}/Th^{232}
Uraninite, Huron Claim—as reported by Nier (1939)	2468	1564	1985	1275
Assuming a loss of 42.1 per cent of the radiogenic lead present in recent geological time, which would not appreciably change the Pb^{207}/Pb^{206} age, we have agreement as follows:				
	2468	2468	2469	2130
Monazite, Huron Claim—as reported by Nier, Thompson, and Murphey (1941)	2590	3217	2938	1827
Assuming a loss of 22.1 per cent of the uranium present in recent geological time which again would not appreciably change the Pb^{207}/Pb^{206} age, we have agreement as follows:				
	2590	2590	2592	....

mathematically meaningless, and the final good agreement of three ages does not prove that the postulated losses are correct. Other arguments must be considered in order to establish the most probable age for a mineral from considerations of the experimental data without any adjustments of that data.

The original findings of Nier (1939, p. 162) and of Nier, Thompson, and Murphey (1941) that ages from the Pb^{207}/Pb^{206} ratio are usually close to the true age of a mineral, even when that mineral had been subjected to alteration and loss of lead or uranium, is still the most important experimental evidence we have. While radon loss has been postulated, it is not probable that Rn^{222} with a half-life of 3.8 days, and with its relatively large atomic diameter, would escape in significant quantities from a mineral. It is true that radon is always found in uranium mines and above surface deposits, but this could be expected when minerals are shattered by blasting or destroyed by weathering on the surface. The interpretation of the age of an altered mineral on the assumption of radon loss has never been proved correct.

Therefore, we consider that the best estimate of the age of the uraninite and monazite samples from the Huron Claim is from Nier's

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Dept. Physics, Univ. of Toronto, Toronto, Ontario, Canada

Manuscript Received by the Secretary of the Society, October 29, 1952

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EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

QUAT — TERTIARY — CRETACEOUS — JURASSIC — U TRIASSIC — UNKNOWN — PLIOCENE? — CRETACEOUS?

- Qt — Terrace gravels
- Tjt — Jutiapa rhyolitic tuffs and sediments
- Tgt — Guacamayas dacitic tuffs and flows
- Tvf — Valle de Angeles formation
- Kp — Plancitos formation
- Kcd — Crucero dacitic flows
- Kct — Colonia andesitic tuffs and breccias
- Kc — Cantarranas formation
- Ju — Undefined Jurassic sediments
- Rep — El Plan formation
- pm — Peten low-grade metamorphics

INTRUSIVE IGNEOUS ROCKS

- Teg — Escobales granodiorite
- Trd — Rancho Quemado dacite
- Taa — Aguacatal porphyritic andesite
- Tra — Reforma hypersthene andesite

Strike and dip of bedding

Strike and dip of foliation

Fold axis

AREAL GEOLOGY OF THE ROSARIO MINING DISTRICT AND THE CENTRAL SAN JUANCITO MOUNTAINS,

Honduras, Central America

UNKNOWN — U. TRIASSIC — JURASSIC

Camarrandas formation

Ju

Undefined Jurassic sediments

Rep

El Plan formation

pm

Peten low-grade metamorphics

INTRUSIVE IGNEOUS ROCKS

CRETACEOUS? — PLIOCENE?

Teg

Escobales granodiorite

Trd

Rancho Quemado dacite

Taa

Aguacatal porphyritic andesite

Tra

Reforma hypersthene andesite

Strike and dip of bedding

Strike and dip of foliation

Fold axis

Fault

Fault inferred

Contact

Inferred contact

Vein

Village

Road

Trail

Stream

AREAL GEOLOGY OF THE ROSARIO MINING DISTRICT AND THE CENTRAL SAN JUANCITO MOUNTAINS,

Honduras, Central America

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 23-38, 2 FIGS., 3 PLS. JANUARY 1954

GEOLOGY AND ORE DEPOSITS OF THE ROSARIO MINING DISTRICT AND THE SAN JUANCITO MOUNTAINS, HONDURAS, CENTRAL AMERICA

By Robert H. Carpenter

Abstract

The Rasario Mining District in south-central Honduras is in the highlands of the rugged San Juancito Mountains. This range consists of a thick section of sediments and volcanics, ranging in age from Upper Triassic to Quaternary, which rests on low-grade metamorphic rocks. It is intruded by plugs and dikes of hypersthene andesites, dacite, and granodiorite. Easterly trending arching, north-south and east-west intrusive trends, and blocks faulting are the dominant structural features.

The extensive, steeply dipping, westerly and northerly trending vein systems, consisting of some 85 veins and splits, have developed largely in the major dacite intrusive body of the district and in the adjacent andesitic tuffs and clastic sediments. The mineralization consists of free gold, sulfides and sulfosalts of silver, and the sulfides of lead, zinc, and copper and related oxidation products. The gangue is largely quartz, rhodonite, carbonates, and country-rock fragments.

The Rosario mines have produced over $93,000,000.00 in silver and gold from some 7,000,000 tons of ore mined since 1883.

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Introduction

The San Juancito Mountains, one of the northwest-trending ranges of the Southern Cordillera of Honduras, are approximately 8 miles northeast of the capitol, Tegucigalpa, and extend for 20 miles along the trend (Fig. 1). The Rosario Mining District is centrally located in the range. The town of Rosario and the Rosario mine are approximately 18 miles from Tegucigalpa on a steep, mountainous road.

The San Juancito Mountains are exceptionally rugged; they rise to 7500 feet in elevation from a base of 2200 feet in the Choluteca valley

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The San Juancito Mountains are exceptionally rugged; they rise to 7500 feet in elevation from a base of 2200 feet in the Choluteca valley

to the northeast, and from 3000 feet in the Tegucigalpa valley on the southwest and west. A steep escarpment has developed on the northeastern slope, whereas the southwestern slope, although deeply incised, is more gradual.

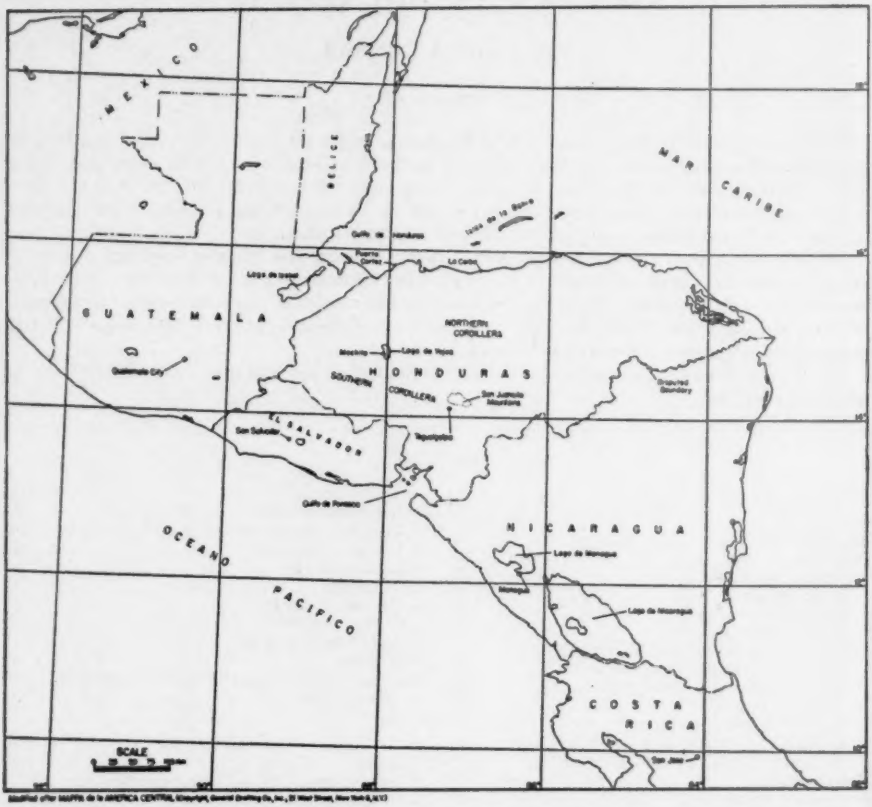


FIGURE 1.—INDEX MAP OF NORTHERN CENTRAL AMERICA SHOWING THE LOCATION OF THE SAN JUANCITO MOUNTAINS

The climate is mild; temperatures range from 40°F to 85°F. The precipitation at Rosario averages between 40 and 60 inches each year; a large part of this falls from early June through October. The dry season, during which there is almost no rainfall, includes March, April, and most of May.

Above an elevation of 5500 feet the San Juancito Mountains are covered with a dense rain forest of giant avocado, oak, and various tropical trees, together with palms, ferns, vines, and shrubs (Carr, 1949, p. 225–226). The intermediate elevations are covered by pine forest and umbrella palm. The vegetation in the semiarid foothill belt and in the valleys consists of small, scattered trees, shrubs, and cacti.

The writer expresses his appreciation to O. H. Rostad, D. L. Moore, and M. C. Godbe, III, for invaluable assistance in mapping the underground and surface geology, and in compiling and correlating the geologic data during the examination of the New York and Honduras Rosario Mining Company properties at Rosario. He also wishes to express his appreciation to F. H. Stephens, K. H. Matheson, C. T. Collins, and other members of the Company management and staff for their assistance with various

phases of the examination.[1] The writer wishes to thank William A. Prendergast, President of the Rosario Company, C. F. Park, Jr., and H. H. Hess for their criticism of the manuscript.

STRATIGRAPHY

General Statement

The San Juancito Mountains consist of sedimentary and volcanic rocks which overlie the low-grade metamorphic rocks of the basement. The minimum thickness of the sedimentary and volcanic section is estimated to be more than 15,000 feet (Fig. 2).

Peten Formation

The well-foliated graphitic and sericitic schists and quartzites of the Peten formation are exposed in the eastern foothills east of San Juancito, in the lower Peten drainage (Pl. 1). The graphitic schists contain numerous pods of milky quartz up to a foot in length, and abundant pyrite casts ¼ to 1 inch in cross section. The sericitic schists grade locally into massive, cliff-forming, medium- to fine-grained quartzites. The regional trend of these rocks is east to northeast. South of San Juancito they appear to form a distorted, westerly plunging anticlinal nose.

There is no evidence as to the age of the Peten formation except that these rocks are overlain by the El Plan sediments (Late Triassic?). They may be metamorphosed Paleozoic sediments, perhaps of Permian age to correspond with the Santa Rosa formation of Chiapas, Mexico, referred to by Eardley (1951, p. 587). Or they may be Triassic deposits, and perhaps even metamorphosed El Plan sediments. The latter does not seem plausible from field relationships, however.

Newberry (1888, p. 345) reports that "beneath the hydromica schists with the plant fossils occur limestones which are said to contain Carboniferous fossils." No limestones younger than Cretaceous were found in the San Juancito Mountains. The plant fossils referred to were collected in somewhat sheared and lithified lower El Plan shales and not in the well-foliated and recrystallized sericitic schists of the Peten formation.

El Plan Formation

The El Plan sediments are best exposed in the vicinity of San Juancito in the eastern foothills, through the Rosario district to the west, and on the southwestern fringe of the range. The exact thickness of these sediments cannot be determined accurately because of poor exposure and because of distortion and alteration from faulting and intrusives.

This formation is made up of alternating members 100 feet or more in thickness. The first consists of banded, dark-gray shale and siltstone beds, ¼ to 2 inches thick, interbedded with a few dark-gray to buff, fine- to medium-grained, poorly sorted, argillaceous sandstone beds, ranging from an inch to a foot or more in thickness. The second consists of gray, poorly bedded, coarse- to medium-grained, 1- to 3-foot sandstone beds, and grit and banded siltstone beds ranging in thickness from a fraction of an inch to several feet. Pebble conglomerate lenses, although rare, are present in both members, and marl beds up to 8 inches thick were noted half a mile northeast of San Juancito.

Plant fossils collected from "metamorphosed argillaceous shales" in the lower part of this formation at San Juancito were determined by by J. S. Newberry (1888, p. 343) as Late Triassic. According to Knowlton (1918, p. 608), however, they are either Late Triassic or possibly Jurassic.

The writer believes this formation was deposited under flood-plain to shallow-marine conditions, and not strictly as intermontane deposits described by Sapper as the Tegucigalpa formation (Weaver, 1940, p. 179). In the opinion of the writer, the red conglomerates described by Sapper and Staub (1937, p. 109) as part of the Tegucigalpa formation are Valle de Angeles beds of probable Late Cretaceous age. The limestone in the same description probably is a part of the Cantarranas formation of Cretaceous age. The red conglomerates appear to overlap the limestone unconformably.

These rocks should be renamed the El Plan

[1] This study, including detailed and reconnaissance mapping of the San Juancito Mountains as a whole, was completed by the geological staff in 1½ years.

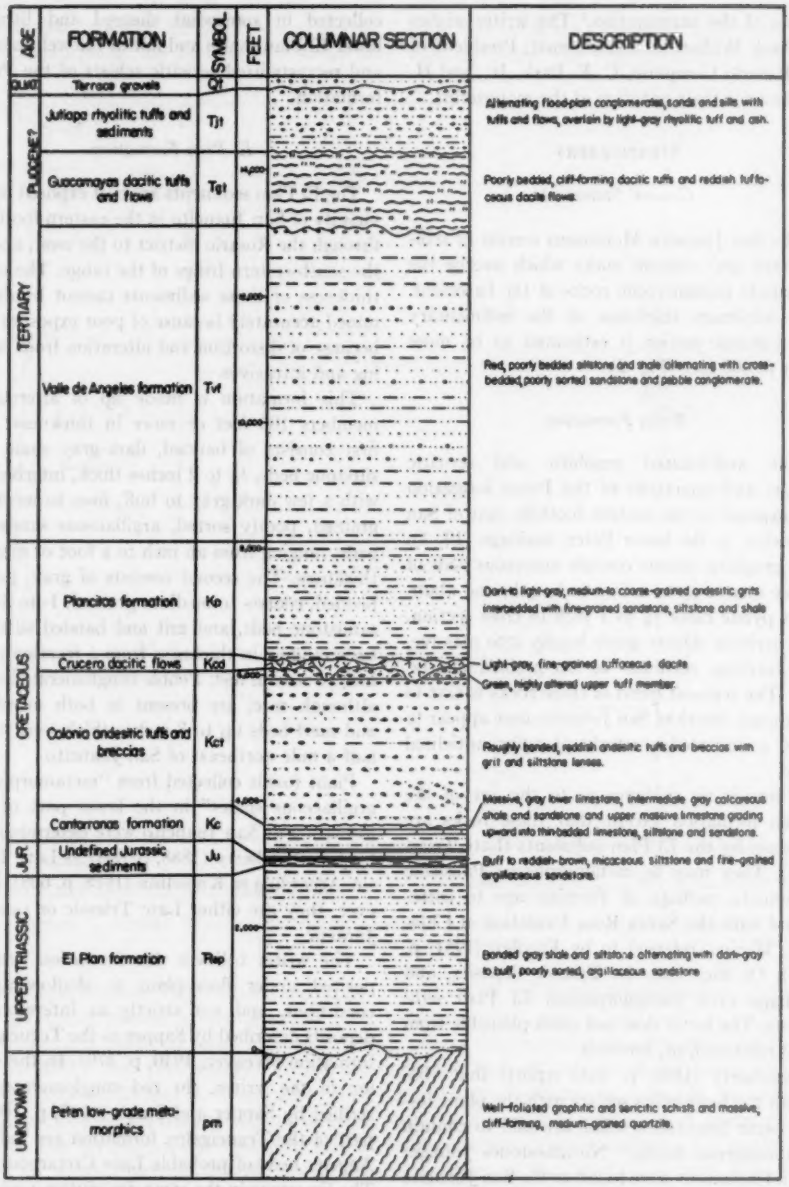


FIGURE 2.—STRATIGRAPHIC COLUMN OF THE SAN JUANCITO MOUNTAINS

formation[2] because of their occurrence at San Juancito and the determination of the Late Triassic (?) plant forms by Newberry from this location. Tegucigalpa is 18 miles to the southwest.

[2] El Plan is a suburb of San Juancito.

Similar shales and sandstones are exposed in erosional windows at Pozo Bendito, 43 miles southeast of San Juancito, and at Sabana Grande, 29 miles south of San Juancito. This formation may have wide distribution in south-central Honduras beneath the cover of the Late Tertiary volcanics.

Undefined Jurassic

In the foothill region approximately 2 miles east of the town of San Juancito are limited exposures of poorly bedded, buff to reddish-brown, micaceous siltstone, and fine-grained, argillaceous sandstone beds that contain numerous *Trigonia* cf. *quadrangularis*, *Gervillia*, and *Meretrix?* of Jurassic age, as determined by K. M. Waage of Yale University. No unconformity has definitely been established between these deposits and the underlying El Plan sediments. An exposed thickness of approximately 100 feet is estimated. These Jurassic sediments have not been recognized with certainty within the Rosario district, but they are believed to be present in the Escobales drainage south of the granodiorite intrusive, an area of intense alteration (Pl. 1). J. J. Barreto, formerly chief geologist for Cia. Minera Agua Fria, of Tegucigalpa, Honduras, reports (Personal Communication) Jurassic marls 12 miles northwest of the Agua Fria mine situated 7 miles northwest of Danli.

Cantarranas Formation

Members of the Cantarranas formation are esposed in an arc from the Assererderro lime kilns, 2½ miles north of Rosario, to the village of Cantarranas, 3 miles northeast of Rosario, along the Choluteca River. These beds have been arched into broad, easterly trending folds that extend from the mountain front to the river. They also are exposed southeast of San Juancito (Pl. 1).

The pertinent characteristics of the formation are:

Upper member:—a. The top 50 feet consists of thin-bedded, dense, gray limestone, calcareous siltstone, and fine-grained sandstone beds 1 to 6 inches in thickness (fossiliferous). b. The lower 75 feet contains massive, poorly bedded, cliff-forming, dense, gray limestone 1 to 20 feet in thickness (fossiliferous).

Middle member:—This member, 345 feet thick, consists of poorly exposed, gray, calcareous shale and medium- to fine-grained sandstone beds from a few inches to 3 feet thick with an occasional dense, gray to buff limestone bed up to 2 feet in thickness.

Lower member:—a. Dense, gray, brittle limestone beds 1 to 4 feet thick with knotty, gray, calcareous shale partings 1 to 6 inches in width occupy the upper 12 feet (fossiliferous). b. The intervening 110 feet is a massive, brownish-gray, poorly bedded, dense limestone with occasional thin shale partings. c. The lower 10 feet (exposed) consists of 1- to 3-foot, dense, gray limestone beds with thin shaly partings well developed.

In the canyon 1 mile northwest of Cantarranas the formation is at least 597 feet thick. *Ostrea*, *Gryphaea* cf. *G. corrugata*, *Pholadomye*, *Crassantellites?*, and an exocycloid echinoid, determined by K. M. Waage of Yale University, were found at Cantarranas in the upper limestone member. Similar, but unidentifiable forms were found in poorly exposed Cantarranas limestone beds on the south flank of the San Juancito arch in the Peten drainage (Pl. 1).

The Cantarranas formation may be an equivalent of the Metapan (Early Cretaceous), described by Weaver (1940, p. 180) in the northern part of the Department of Tegucigalpa (Francisco Morazan).

Colonia Andesitic Tuffs and Breccias

Reddish to greenish andesitic tuffs and breccias are well exposed in the eastern sections of the mine and northeastward for 2 miles. The tuffs consist of broken feldspar and ferromagnesian crystals, andesite fragments of variable size and shape, and lapelli embedded in altered glass shards and ash. In the breccias, angular to subrounded rock fragments which range up to a foot or more in diameter are embedded in altered tuff and ash and make up as much as 50 per cent of the rock. Both the tuffs and breccias contain charred twigs. Lenselike graywacke and grit beds, from a few inches to several feet thick, are found within this unit. These beds consist almost entirely of andesitic debris and grade laterally into tuffs.

In the vicinity of the mine these volcanics rest unconformably on the El Plan sediments

and appear to grade eastward into the lower Plancitos sediments. They reach a maximum estimated thickness of 3000 feet along the eastern fringe of the mine area and are believed to be Cretaceous but they may reflect Nevadan vulcanism in this region.

A greenish, highly chloritized, albitized, and sericitized andesitic tuff member ranging from 50 to 100 feet in thickness overlies the andesitic tuffs and breccias. This unit also contains lenses of clastic andesitic sediments.

Crucero Tuffaceous Dacite Flows

A light-gray, well-sericitized, fine-grained, somewhat tuffaceous dacite flow has filled channels and depressions on the greenish tuff surface. The phenocrysts average 1 mm in diameter and consist of andesine, quartz, and biotite. They are embedded in a finely crystalline to glassy matrix consisting of small feldspar laths, embryonic crystal growths, glass shards, and ash.

These flows are exposed underground along the western fringe of the mine and in the headwaters of Crucero Creek immediately north of the mine. They total more than 400 feet in thickness and are overlain by greenish andesitic tuffs of the upper member of the Colonia andesitic tufls and breccias, indicating continued deposition of this aerial debris.

Plancitos Formation

Underground and on the surface along the western and northwestern fringes of the mine area, a thick section of clastic sediments is exposed. These sediments, which are best exposed in the vicinity of the Plancitos sawmill, are here referred to as the Plancitos sediments.

They consist largely of fairly well bedded, dark- to light-gray, medium- to coarse-grained grits, together with alternating beds of poorly sorted, fine-grained sandstone, siltstone, and shale. The medium- to coarse-grained grits contain broken feldspar and ferromagnesian grains and sub-angular fragments of andesite, quartz-bearing lava, graywacke, silty shale, quartzite, sparse limestone, and schist. These grade into extensive conglomerate lenses with boulders up to 2 feet in diameter. The interbedded fine sandstone, siltstone, and shale beds range in thickness from half an inch to 1 foot, whereas the grit beds and conglomerate lenses range from a few inches to several feet. Cross-bedding, lensing, and channeling are common in the grits. Poorly preserved, unidentified leaf imprints were found in the silts and shales.

The Plancitos sediments, which consist largely of reworked andesitic debris, are continental. The formation is believed to be Cretaceous, representing reworked andesitic tuffs and breccias deposited in the flanking areas. The exposed thickness is 1900 feet, but the total thickness may exceed 4000 feet as indicated by the distribution of a few outcrops along the eastern fringe of the range beneath the extensive cover of Jutiapa rhyolitic tuff.

Valle de Angeles Formation

Most of the southern third of the San Juancito Mountains consists of red, poorly bedded sediments herein designated the Valle de Angeles formation. On the western slope of the mountains, red shales, siltstones, and fine-grained sandstones predominate, whereas on the eastern slope, in the vicinity of the Valle de Angeles, pebble conglomerates and red sandstones make up most of the section. The sandstones are poorly sorted and consist of subangular to sub-rounded quartz grains, ⅛ to 2 mm in diameter, with a siliceous and ferruginous cement. A few quartz pebbles are included. The pebble conglomerate beds consist largely of subangular to subrounded quartz pebbles, ¼ to 1 inch in diameter, embedded in a matrix of coarse- to medium-grained sand bound by a siliceous cement. Pebbles of altered sediments, volcanics, quartzite, and schist also are present, representing all older rock types exposed in the region. These deposits are continental and probably represent intermontane deposition, with an immediate highland source area to the east.

This formation is estimated to be at least 10,000 feet thick and may be much more. These southerly dipping beds are believed to be Late Cretaceous or possibly Early Tertiary because they overlie upturned limestone beds of the Cretaceous Cantarranas formation and in turn are overlain unconformably by the flat-lying, late Tertiary Jutiapa rhyolitic tuffs. Their regional trend roughly parallels the axis of the San Juancito arch. These red beds are well exposed along the southeastern flank of the

arch and in the adjacent syncline south of the village of Valle de Angeles. They are intruded by the hypersthene andesites.

Guacamayas Dacitic Tuffs and Flows

Immediately north of the Rosario district, reddish, tuffaceous dacite is widespread along the eastern escarpment of the range. It is a porphyro-aphanitic rock of dacitic to rhyolitic composition with numerous fragments of tuff, andesite and pumice, and other rock inclusions. The phenocrysts consist of quartz, andesine, biotite, and sparse potash feldspar ranging from 1 to 5 mm in diameter embedded in a matrix of glass shards, ash, and occasional small feldspar laths. This dacite is believed to consist of both flows and aerial debris and may have been extruded from the smaller Rancho Quemado dacite intrusive body situated in Crucero Creek immediately northeast of the main body of the mine area. These tuffs and flows rest unconformably on the Colonia andesitic tuffs and breccias, the Plancitos formation, and the Cantarranas formation.

Jutiapa Rhyolitic Tuffs and Sediments

On the western slope of the range, flat-lying siltstones, sandstones, and conglomerates overlie steeply dipping Valle de Angeles red beds and older sediments. They are believed to be late Tertiary (Pliocene?) flood-plain and alluvial-fan deposits interbedded with rhyolitic flows and tuffs (Schuchert, 1935, p. 353). They grade upward into volcanic rocks consisting largely of rhyolitic tuff, containing shattered quartz, feldspar, and biotite phenocrysts, and fragments of pumice and other volcanic debris embedded in a matrix of ash and glass shards. Dense white to pink ash beds up to 10 feet thick are interbedded with tuff 2 miles south of Rosario. Stream channeling and slumping developed within these beds during deposition.

These beds dip gently northwest and are at least 1000 feet thick. Remnants of these tuffs cover the higher ridges and peaks in the southern part of the San Juancito Mountains, most of the northern and northwestern sections of the mountains, and the extensive highlands to the northwest. These beds probably are the same age as the volcanics which cover much of southern Honduras.

Numerous plant forms were collected from ash and tuff beds in the upper Escobales drainage, but they have not yet been determined.

Intrusive Rocks

General Statement

Five intrusive rock types have been found within the intrusive center surrounding Rosario: fine-grained hypersthene andesite; porphyritic, quartz-bearing, hypersthene andesite; biotite dacite; biotite granodiorite; and narrow dikes of coarse-grained granite (?).

Reforma Hypersthene Andesite

The fine-grained hypersthene andesite, the oldest intrusive, forms the south wall of the Rosario vein and is extensively exposed eastward in the vicinity of San Juancito and northward along the foothill belt. It also intrudes the sediments on the western slope of the range near the Aurora prospect. This intrusive is named after the small village of Reforma immediately below the mine plant.

This rock is porphyro-aphanitic with a few 2- to 3-mm andesine and hypersthene phenocrysts, and sparse augite phenocrysts embedded in a dense matrix. Sericitization generally is intense, making mineral identification difficult.

This andesite intrudes the sedimentary section up through the Valle de Angeles red beds but is covered by the Jutiapa tuffaceous deposits. It is intruded by the porphyritic hypersthene andesite.

Aquacatal Porphyritic Andesite

Porphyritic, quartz-bearing, hypersthene andesite is widespread along the southern fringe of the district, particularly in the central part of the range immediately south of the mine workings in the vicinity of the aquacatal tunnel (Pls. 1, 3).

This rock also is porphyro-aphanitic, but it contains numerous large andesine and hypersthene phenocrysts up to 6 mm in length, some augite, and sparse biotite and quartz phenocrysts. The matrix consists large of devitrified glass with clusters of embryonic crystal growths.

Exposures of this intrusive range from a fresh, hard, brittle, dense, dark greenish-gray rock to a highly altered, soft, claylike mass, or an extremely hard, somewhat porous, silicified rock. It intrudes all the stratified rocks except the flat-lying Jutiapa rhyolitic tuffs which cap the higher parts of the range.

Rancho Quemado Dacite

Greenish-gray to gray biotite dacite, which acts as a host for more than half the productive veins in the district, has intruded the underlying andesitic tuffs and breccias and the overlying Plancitos sediments as an elongate, north-south trending plug approximately 2000 by 6000 feet in dimension. This plug rakes westward roughly parallel to the dip of the sedimentary rocks. A smaller dacite intrusive body outcrops to the north between Crucero and Sapote creeks (Pl. 1), and a third may be covered by the Jutiapa rhyolitic tuffs of the Peña Blanca promontory area south of the mine workings.

This biotite dacite is porphyro-aphanitic, and quartz, plagioclase, and biotite phenocrysts are embedded in a dense to finely crystalline matrix. The quartz averages about 2 mm in diameter, whereas the plagioclase (andesine) and biotite range between 1 and 2 mm. The groundmass is largely devitrified glass, particularly along the borders of the body. Ten to 30 per cent consists of a mat of fine, embryonic crystals.

The rock is extensively sericitized, chloritized, and pyritized throughout the mine area, and locally it is silicified and kaolinized along veins and mineralized joints. Along the upper contact with the greenish, upper member of the Colonia andesitic tuffs and breccias and the Plancitos sediments is a pinkish alteration zone ranging up to 50 feet in width. It is present both in the chilled border zone of the dacite and in the intruded rocks. According to A. C. Waters[3] (Personal Communication) it consists largely of microscopic veinlets of carbonate, possibly siderite or ankerite, with about 20 per cent of fine-grained pyrite. The iron-bearing carbonates have been oxidized to release a pinkish hematitic stain. Moderate silicification accompanies this alteration locally.

Subangular to subrounded "boulders," "cobbles," and "pebbles" of volcanic debris are distributed throughout the dacite along irregularities of the "floor" of the main dacite body and locally along the "hood." This debris consists of inclusions and of the fractured, chilled border zone of this intrusive, rounded by abrasive action resulting from drag effects of circulation in the still-liquid portions of the intrusive. Waters suggests that accumulation of this debris may occur along irregularities in the contact where the circulation of the magma is less rapid. Perhaps the accumulation is enhanced by shearing across the contact which made available to the circulation circuit country-rock fragments and blocks of the chilled border. "Cobbles" and "pebbles" of porphyritic hypersthene andesite are among the inclusions in the dacite.

Escobales Granodiorite

Granodiorite is poorly exposed in an area approximately 1000 feet by 4000 feet in the thickly vegetated Escobales drainage along the southern edge of the Rosario district.

This rock consists of interlocking phenocrysts of plagioclase, biotite, and augite, which range from 1 to 4 mm long, and quartz and orthoclase, which seem to fill the interstices and average less than 1 mm in length. The quartz is in small phenocrysts and intergrowths with orthoclase. Together they make up 10 to 15 per cent of the rock. Outcrops of the granodiorite are relatively fresh except for the augite which is almost completely altered to chlorite and magnetite.

The granodiorite has intruded the El Plan sediments along the axial zone of the San Juancito arch. It appears to intrude the Aquacatal porphyritic andesite, but this relationship has not been proved. It grades laterally into a more porphyro-aphanitic phase along its borders and probably represents the hood of a relatively near-surface intrusive. Extensive exposures of biotite granodiorite in the vicinity

[3] Professor A. C. Waters, of Johns Hopkins University, completed petrographic studies of Rosario specimens for the writer during the geological examination of the district and offered many important suggestions regarding intrusive relationships.

of the Agua Fria mine near Danli are approximately 35 miles southeast of Rosario along the southern fringe of the Chile Mountains.

Granite (?) Dikes

Granite (?) dikes up to 20 feet wide are exposed in the Escobales drainage within and in the adjacent contact-alteration halo of the granodiorite intrusive. They may represent late-phase dikes from the same source magma as the granodiorite. These coarse, phanerocrystalline dikes contain quartz, orthoclase, plagioclase, and biotite phenocrysts which average approximately 10 mm in diameter. Alteration has been very intense; consequently the ratio of the feldspars is difficult to determine.

General Intrusive Relationships

One batholith of intermediate composition may underlie the entire San Juancito Mountain region, with the early hypersthene andesites and the later dacite and granodiorite types as differentiates. Dikes and plugs of early hypersthene andesites and somewhat later dacite may represent initial near-surface penetration and perhaps even surface volcanism, whereas the granodiorite stock of the Escobales drainage may be a cupola representing a late, high penetration of the batholith into the hood. If the extensive silicification of the Jutiapa tuffs occurred during the above period of intrusive activity, the intrusives are post-Jutiapa or Late Tertiary. If not, they and the Plancitos grits probably are Late Cretaceous to correspond with the volcanics and graywackes of similar composition found in the Caribbean area as a whole (H. H. Hess, Personal Communication).

A second possibility is that the andesitic intrusives may be Late Cretaceous, and a part of the same period of volcanism that resulted in the deposition of the Colonia andesitic tuffs and breccias and the andesitic Plancitos sediments. The Rancho Quemado dacite, the Escobales granodiorite, the Guacamayas dacitic tuffs and flows, and the Jutiapa rhyolitic tuffs may represent a late Tertiary stage of volcanism. The silicification of the Jutiapa tuffs and the metallic mineralization appears to be related to this stage of intrusive activity.

Structural Geology

Regional Structure

In the San Juancito Mountains the major structural features include: northeast-southwest arching, east-west and north-south intrusive trends, and block faulting developed on north-south, northeast-southwest, and east-west trends.

The broad northeast-southwest arching is illustrated in the distribution and attitudes in the El Plan sediments (Pl. 1). These Late Triassic (?) rocks are well exposed from the Guadalupe power plant east of San Juancito southwestward through the Rosario district and again on the western slope of the range in the foothill belt of the San Juan Creek drainage. The arching is indicated by northerly dips predominating in the vicinity of Rosario and westerly to southerly dips on the Lempira ridge and the Esobales drainage to the south. In San Juan Creek the dip is gently southwest, whereas, immediately to the south, the dip steepens to the south. This arch developed early in the structural history of the region, probably in Nevadan time, and was intensified in Laramide and to a lesser degree in the Tertiary prior to the intrusive activity and faulting in the late Tertiary. It probably reflects the regional easterly trend of the ancient Antillean geanticline (Schuchert, 1935, p. 351).

Intrusive trends within the Rosario intrusive center reflect the failure of the broad arch. The early hypersthene andesite intruded the east-west zones of weakness as dikes and irregular plugs. The granodiorite also is elongated in an east-west direction. The dacite exposed along the crest of the mountains trends north-south both in the main body and in the subsidiary plug to the north in the Sapote Creek area. The exposures of the porphyritic hypersthene andesite south of the Rosario mine workings form a roughly circular pattern.

The localization of the intrusive rocks within a relatively small center along the San Juancito arch on an obvious east-west north-south structural crossing probably reflects large-scale structural intersection at depth. Much of central Honduras may be underlain by batholiths of intermediate composition, and Rosario, Yus-

caran to the south, Agua Fria to the southeast, and the Chile Mountains to the east may be focal points of weakness through which the magma escaped to the surface. All the above areas are within 30 miles of Rosario.

Post-intrusive block faulting, controlled by faults of steep dip, is well developed along the eastern front of the mountains; most of the faults trend north, northeast, and east (Pl. 1). A block of schists and quartzites has been uplifted and exposed by erosion immediately southeast of San Juancito. It is outlined on the north and on the south by transverse faults, whereas on the west it is flanked by the San Juancito fault zone which extends southerly along the mountain front west of the Valle de Angeles for several miles. The downthrown side along this major zone is on the west or mountain side. The upthrown, foothill side has been eroded to moderate relief. The high relief of the main ridge to the west is a result of greater resistance to erosion caused by the profound alteration of the rocks within the intrusive center of the Rosario district.

The gently folded Cantarranas limestone beds have been downdropped along an east-west transverse fault 1½ miles north of Rosario. Easterly trending transverse faults across the northerly trending ridge line are a common feature in the higher parts of the range, but well-developed block faulting is absent.

The block faulting along the eastern front of the range consists of north-south step faults, east-west transverse faults, and related northeast shears. This broad structural adjustment took place largely after the deposition of the most recent of the Jutiapa rhyolitic tuffs which cap the range, although there is definite evidence of pre-Jutiapa faulting of probable Laramide and possibly Nevadan age. Certainly faulting accompanied the metamorphism, and contortion of the Petan metamorphic rocks, but the evidence is obscure.

Local Structure

The highly productive mine area is enclosed in the Rosario mine structural block. The southern edge is defined by a steeply dipping, east-west trending, transverse fault which has an estimated throw of more than 500 feet. On the north this block is outlined by an east-west hypersthene andesite dike extending westward to the San Miguel area along Crucero Creek. Related east-west shearing continues westward into the Rio Hondo drainage on the west side of the range.

Northwest joints are well developed throughout the block. The strike averages N. 30°–60° W., and the dip is variable but steep. Northeast joints are subsidiary. The joints are tight and generally unmineralized, but locally they have acted as channels for the hydrothermal solutions which formed the blanket sericitization, chloritization, and pyritization of the mineralized area.

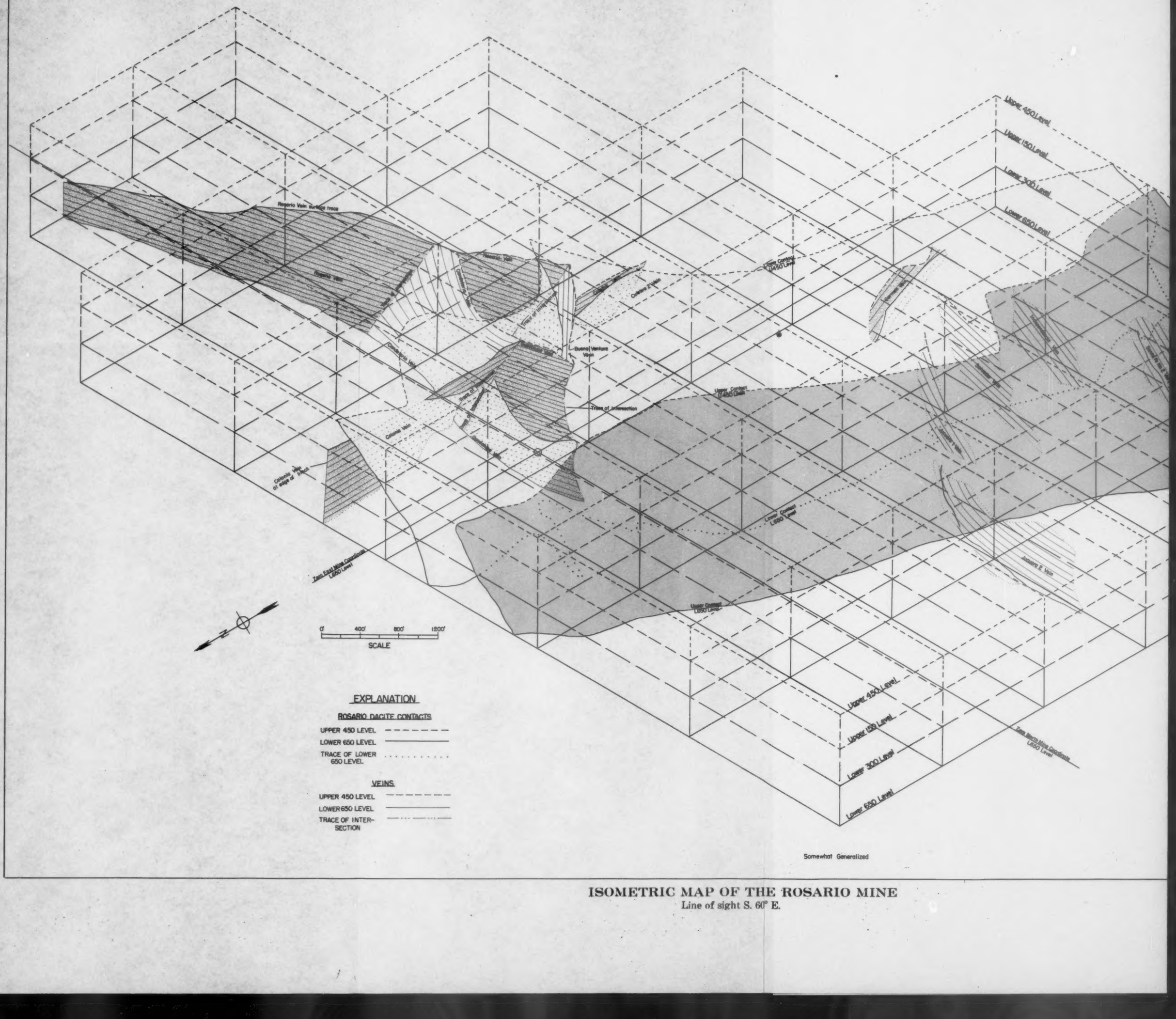
The dacite body and the underlying andesitic tuffs and breccias reacted under stress as a competent but brittle area. Two fracture systems developed: those roughly normal to the trend of the dacite body, and those roughly parallel to it. The former consist of a composite pattern of shears; the latter ragged, somewhat discontinuous, "tensional" structures. Mineralizing solutions flooded these channels to form the veins (Pl. 2).

Post-mineral faulting is essentially absent in this area except along the contact between the dacite body and the overlying Plancitos sediments, and along the Buena Ventura and Guadalupe fault veins. In both instances the adjustment has been small. The maximum offset of veins crossing the upper, sedimentary contact is 15 feet.

Ore Deposits

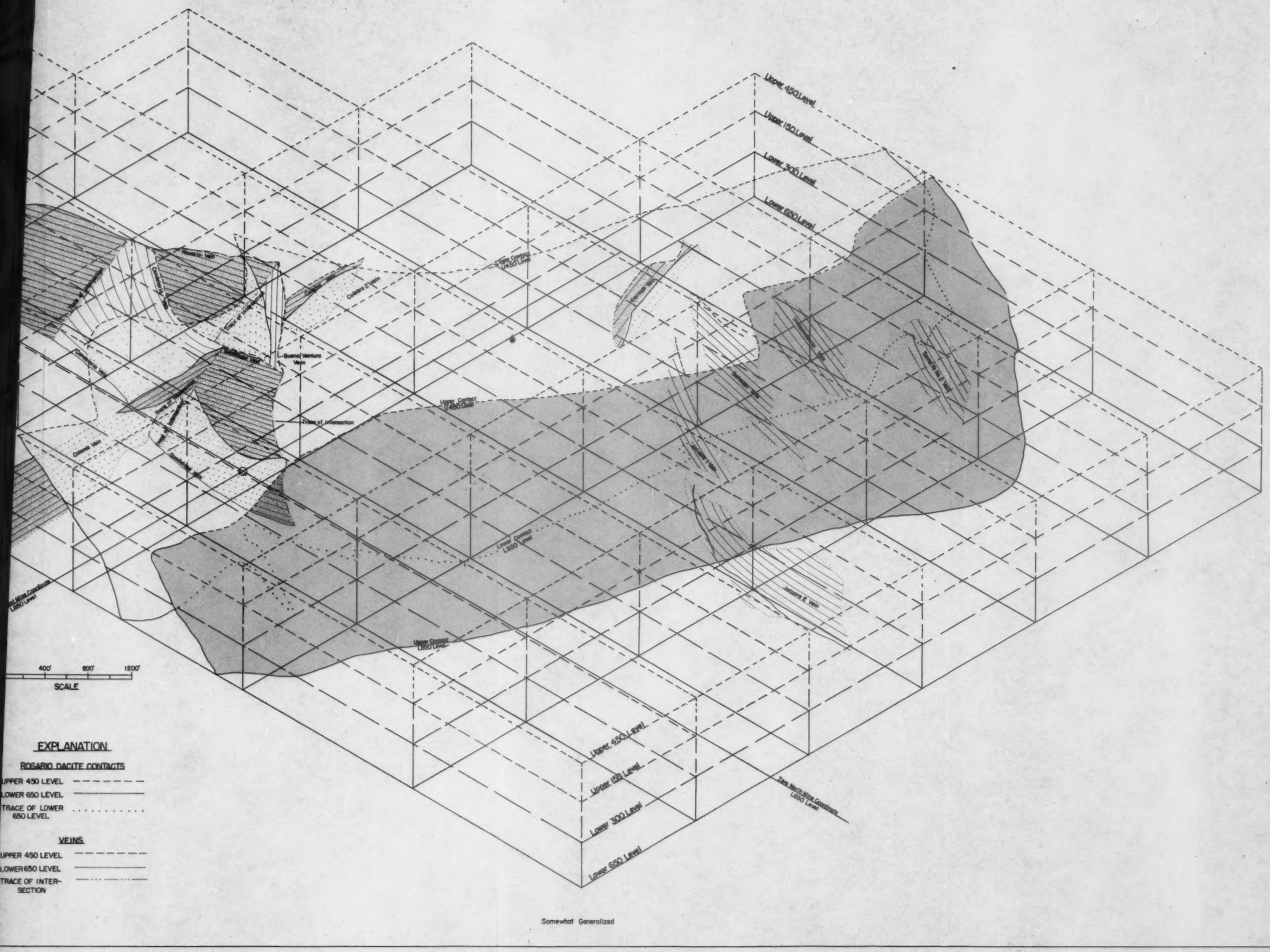
General Statement

Mineralization in the San Juancito Mountains is concentrated in the northern and western parts of the intrusive center surrounding Rosario, except for three small prospects on the southern fringe. The veins developed for 7000 feet north-south from the San Miguel area to the Santa Fe, and 12,000 feet east-west from the Rosario plant to the Jucuara area within the Rosario mine structural block. All the intrusive rocks except the granite dikes are mineralized, as are the intruded rocks. The great concentration of productive veins is in the main dacite body, in the Plancitos sediments to the west, and in the andesitic tuffs and breccias to the east.



ISOMETRIC MAP OF THE ROSARIO MINE

Line of sight S. 60° E.


Upper 450 Level
Upper 150 Level
Lower 300 Level
Lower 650 Level
Upper Contact 1450 Level
Lower Contact 1650 Level
Upper Contact 1650 Level
Trace of Intersection
Buena Ventura Vein
Rosario Vein
Jaegers E. Vein
Jaegers W. Vein
Consuelo Vein
Consuelo 2 Vein
Consuelo 3 Vein
Consuelo 4 Vein
Consuelo 5 Vein
Consuelo 6 Vein
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Vein Development in the Productive Area

Within the productive area of the Rosario mine, approximately 85 veins and branches have yielded a total gross production of over $93,000,000.00.

These veins have a vertical range of as much as 1800 feet and a length up to 2000 feet, except for the Rosario vein, which extends eastward more than 6000 feet. They are strongest in the dacite and the underlying andesitic tuffs, with the exception of the Jucuara 2 and related veins, which formed in the Plancitos sediments west of the dacite. The distribution of the veins and their relationship to rock types is illustrated on the isometric map of the Rosario mine (Pl. 2) and on vertical cross sections through the productive area (Pl. 3).

Five major vein systems are known in the mineralized area: (1) Rosario-Buena Ventura-Candelaria-Guadalupe system, (2) San Miguel South-Colonia-Culebra system, (3) Southwest system, (4) Jucuara 2 system, (5) Salvador-Jucuara 1-Independencia-Santa Fe system.

The eastward-trending, northward-dipping Rosario vein formed along the contact between the fine-grained hypersthene andesite and the adjacent San Juancito sediments and andesitic tuffs. The northwestward-trending, northward-dipping Guadalupe and Buena Ventura fault veins developed along the "flanks" of a high in the andesitic tuffs underlying the dacite (Pl. 3).

The eastward-dipping San Miguel South, Culebra, and Colonia veins can be considered ragged "tensional" structures developed along a north-south trend roughly across the trend of the Buena Ventura-Guadalupe system of fault veins.

The Southwest system of mineralized fractures ranging up to 6 inches in width developed at the junction of the east-west Rosario trend with the north-east trend of the dacite-sedimentary contact. Irregularities in the contact appear to have controlled the formation of the individual veins.

The Jucuara 2 system is an extension of the westward Rosario trend along the southern flank of a local, westward-trending anticline in a highly clastic horizon of the Plancitos sediments.

The steeply dipping, east-west trending Salvador, Independencia, Jucuara 1, and related veins appear to intersect to the southeast in an area of jogs in the dacite-andesitic tuff contact. In addition, a dike of porphyritic andesite projects into the area of intersection from the east on the U 150 and L 300 levels. These irregularities and the presence of the andesite dike may have been factors in localizing these veins and establishing their trends.

The Santa Fe veins, which are farther south with a similar east-west trend, are a composite group consisting of steeply dipping veins and of relatively flat, northerly dipping veins. All roughly parallel the eastward swing in the contact between sediments and dacite. The Santa Fe No. 4 and Santa Fe Main veins have a gentle dip approximately normal to the southerly dip of the contact.

Detailed mapping indicates that most of the veins either break up and lose their identity on the lower levels of the mine or contain lower percentages of silver and gold. Exceptions include the following: On the western edge of the mine the Jucuara 2 vein is well defined and productive to the L 850 level, and the Santa Fe veins extend to the L 750 level on the southern edge of the productive area. The Rosario veins at and for some 600 feet east of its intersection with the Candelaria vein on the L 1150 level is well mineralized with copper, lead and zinc sulfides, and moderate silver values for widths ranging from a few inches to 5 feet. Other veins which continue in strength at depth do not contain appreciable base-metal sulfides.

Extent of Ore Shoots

The remarkable production of the Rosario mine has been derived largely from 10 or 12 of the larger, more persistent veins of the district. The main ore shoot of one of these important producers, the Salvador vein (Pl. 2), extends from the L 500 level to above the U 650 level, a vertical distance of more than 1185 feet. The maximum length of this ore shoot exceeds 2000 feet, and the average width is 5 feet. The ore zone in the Jucuara 2 vein extends from the L 750 level to above the U 150 level, a vertical distance of 963 feet. Its maximum length is 2200 feet, and its average width is 3 to 4 feet. Another large producer is the Colonia vein

which extends from the L 500 level to the surface above the U 1000 level. Others are less extensive, narrower, and less uniform.

Local Controls

The more obvious controls influencing the rake of, strength of, and values within the ore shoots are the: (a) Type and extent of the original structure, (b) Nature of the vein, whether largely vein filling or replacement, (c) Irregularities in trend of the fracture both on strike and dip, (d) Contacts and rock types, (e) The relative concentrations of silver and gold, values in relation to base-metal sulfides and gangue minerals, (f) The type and extent of pre-mineral alteration.

The following observations regarding the above factors concern the more productive veins of the district:

(a) The Buena Ventura, Guadalupe, Southwest, and 56 fault vein formed in or along zones of shearing. The north-trending Culebra, Colonia, and San Miguel veins, on the other hand, are weak, tensional openings with little or no faulting involved in their development. They are ragged, locally discontinuous zones of cracking. Essentially, this is true of most of the veins of the district. The offset on the Buena Ventura and Guadalupe faults is largely pre-mineral, and before the development of the Culebra-Colonia system which crosses the former at right angles. There is little or no offset on the latter, and the widths and values in many of these veins diminish at or near the intersection, probably as a result of a release of the effective stress along the Buena Ventura and Guadalupe zones.

(b) The Candelaria, San Juaquin, and Capitana veins were formed by filling of fractures, whereas the north-trending Colonia, San Miguel, Cuelebra, Crisanta 2 and 3, as well as the Carmen, were developed by replacement of the wall rock adjacent to weak, somewhat discontinuous irregular fractures. The ore shoots along the strike of these veins are erratic but fairly persistent on dip.

(c) Most of the veins in the Rosario mine are composite and consist of alternating segments of two or more trends. For example, the composite Santa Fe 4 vein, at the southern edge of the mine, consists of alternate, almost east-west and northwest segments. The widths and values are erratic along the general trend, and the vein is usually weak where the trend changes. The ore shoots in the Santa Fe 4 vein both fill the fracture zone and replace the country rock in areas most readily accessible to the ore-bearing solutions. The hanging wall of this vein appears to have moved down dip, but the offset is slight.

(d) In the district are many examples of the direct influence of contacts and rock types on the formation of the veins. The Southwest fault vein developed along the contact between the dacite and the Plancitos sediments. The Jucuara 1 vein on the L 300 level breaks up where it passes eastward from the dacite to the andesitic rocks. The main Salvador vein on the U 150 level dies out westward toward the sedimentary contact. Similarly, the Jucuara 2 system does not continue eastward from the sediments into the dacite except as a narrow fracture, and the Santa Fe No. 4 vein extends upward only a few feet from the dacite into the sediments. Many veins extend from the dacite into the andesitic tuffs and breccias with little change where the competency of the two rocks is similar.

(e) The concentration of silver and gold in relation to other minerals in a vein also is a factor in the formation of the productive ore shoots. The only absolute relationship between the width of the vein and the concentration of silver and gold is that most of the ore shoots are in the wider, more open segments of a vein. The narrow, tight sections commonly contain a low percentage of silver and gold relative to the base-metal and gangue content.

The base-metal content of the veins is low except locally. On the L 1150 level where the base-metal content of the Rosario vein is appreciable, the gold and silver values are low. This may represent one of several main feeder channelways from depth. The concentration of silver and gold deposition from the ore-bearing solutions appears to have developed in the best-formed parts of the ore shoots which, in general, are above the L 650 level.

(f) Hydrothermal alterations has been moderate to intense along the Independencia vein in the southern part of the mine. This alteration is believed to be largely pre-mineral and has weakened the dacite sufficiently to make it less favorable for vein development.

Other controls such as the pH of the ore-bearing solutions, the degree of susceptibility of the wall rock to replacement, possible electro-potential factors, pressure-temperature controls, etc., also may have influenced the development of the ore shoots. Specific data on these factors are not available.

Mineralogy

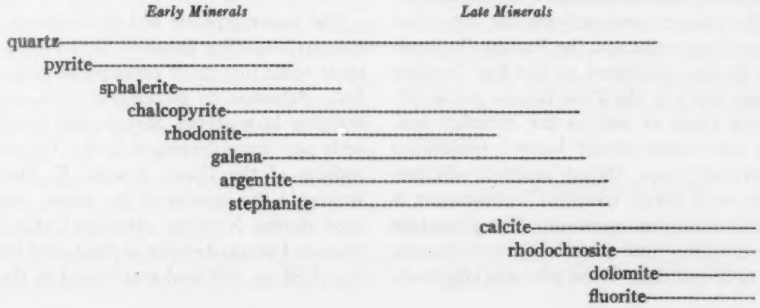
General Discussion

Throughout the district quartz, pyrite, rhodonite, calcite, and altered country-rock fragments make up most of a vein, with sphalerite, chalcopyrite, and galena in variable proportions to each other and to the gangue minerals. Argentite, stephanite, the ruby silvers, and native silver, together with native gold, occur as minor primary constituents. Rhodochrosite, dolomite, fluorite, and gypsum also were noted as very minor constituents.

The veins on the northern side of the mine contain very little rhodonite and only a moderate amount of chalcopyrite, whereas the Salvador-Santa Fe vein system is characterized by a relatively high percentage of these minerals.

The Capitana and San Juaquin veins have produced gold in a silver-gold ratio of approximately 45 ounces of silver to 1 ounce of gold and 65 ounces of silver to 1 ounce of gold, respectively, whereas the San Benito 2 and Santa Fe 4 veins have produced gold in a 78 to 1 and 88 to 1 ratio. Past production records give an overall ratio of 180 ounces of silver to 1 ounce of gold.

The paragenetic relationships among the important vein minerals are as follows:



Native silver, pyrargyrite, prousite, anglesite, cerussite, smithsonite, malachite, azurite, and the iron and manganese oxides occur as oxidation products in variable amounts in the oxidized parts of the veins.

Intermediate temperature-pressure conditions prevailed during the formation of the veins. The minerals are intergrown in a roughly banded pattern, with the later ore and gangue minerals cutting across and replacing the earlier. In many places more than one stage of the same mineral assemblage is evident. Late quartz and calcite frequently form a network of stringers within and adjacent to the veins and fill open spaces or line small vugs. The stringers commonly offset the vein banding a fraction of an inch. Vein reopening has resulted in brecciation, with later vein material filling around the fragments.

Overall Control of Vein Formation

Intrusive activity, the structural development of the range, and vein formation appear to be intimately related. Vein formation apparently depended upon the shattering of the competent Rancho Quemado dacite, the Colonia andesitic tuffs and breccias, and the more brittle portions of the Plancitos sediments. Certainly the availability of ore-bearing solutions as a late-stage segregate of an underlying, cooling batholith also was a prime prerequisite.

Age of Mineralization

The deposition of the ore in the Rosario veins probably postdates all the sedimentary, intrusive, and volcanic rocks of the range except the upper beds of the Jutiapa rhyolitic tuffs. The basal beds of these flat-lying tuffs of Plio-

cene (?) age which cap the range above the highly productive area along the western side of the mine have been mineralized and altered by hydrothermal solutions. Probably this mineralization represents the upper fringe of a single period of mineralization during which the veins of the district were formed. In the opinion of the writer the vein development represents a late stage of the granodiorite-dacite phase of the intrusive activity of the area.

A second possibility is that all intrusive activity in evidence in the area occurred in the Late Cretaceous together with the main mineralization. The veinlets in the Jutiapa tuffs, in this case, would in all probability represent a weak period of mineralization unrelated to the main period.

Alteration

The entire Rosario intrusive center extending from San Juancito on the east to the western fringe of the mine, and from the southern edge of the Escobales drainage to Sapote Creek on the north, has been affected by blanket sericitization, chloritization, pyritization, and kaolinization. Hydrothermal solutions from deep-seated sources saturated and replaced rocks of all types within the range. Probably hydrothermal solutions related to each successive phase of igneous activity effected in a greater or lesser degree the widespread alteration in the area. Alteration effects have been noted adjacent to the andesitic dikes, the granodiorite, and around the fringes of the dacite intrusive bodies. Field evidence suggests the source of the alteration solutions was in many instances the adjacent dike or intrusive body.

The most intense alteration in the district is in the contact zone between the Aguacatal porphyritic andesite and the Rancho Quemado dacite in the headwaters of the San Juancito drainage south of the Pena Blanca portal (Pl. 1). Both types as well as the intruded sediments have been altered beyond recognition in restricted areas. Almost complete silicification to very nearly complete kaolinization is present in individual specimens. The percentage of pyrite within these areas is higher, increasing to 20 to 25 per cent. These products effectively mask the blanket sericitization and chloritization of the district and appear to be late in the alteration sequence.

The Jutiapa tuffs in the headwaters of the Escobales drainage have been intensely silicified to form a reeflike, cliff-forming front from the Rancho Quemado summit on the Tegucigalpa road southeastward to Volcan del Valle (Pl. 1). The distribution of this intense silicification is within the area intruded by the larger of the Aguacatal porphyritic andesitic plugs. The silica-bearing solutions may have percolated upward into the tuffs during this phase of the intrusive activity, but it is more probable that they were derived from the granodiorite-dacite phase. Also, the porphyritic andesite is intensely silicified and altered in the vicinity of the dacite intrusive body and along the western edge of the granodiorite stock.

The alteration halo adjacent to the veins as silicification, sericitization, kaolinization, and pyritization is believed to be mainly premineral, developing outward from the fracture, but in part simultaneous with vein development. This halo effect ranges from a fraction of an inch to several feet depending upon whether the vein development was largely filling or replacement. Generally, the alteration is more intense with the latter. Locally, ore-bearing stringers have developed outward into the alteration halo. Detailed investigations of the Rosario alteration halo relationships are in progress. Alteration relationships both at Butte, Montana, and at Tintic, Utah, have been worked out in great detail. The reader is referred to Sales and Meyers (1950) and Lovering (1949).

Summary of the Regional Structural Framework

The metamorphism and development of the eastward-trending lineation of the Peten basement rocks may have occurred as early as the Late Paleozoic to correspond with mountain building in southern Mexico and Guatemala, or it may have developed in the Triassic. The arching of the Upper Triassic El Plan sediments, in the opinion of the writer, was initiated during Nevadan structural adjustments through Central America as illustrated by Eardley (1951, p. 595) and reactivated in the Lara-

mide as a recurrent fold with Late Cretaceous volcanism as an intermediate step. This folding also is reflected in the Valle de Angeles formation of probable Late Cretaceous to Early Tertiary age, but it is not reflected in the Jutiapa formation of Late Tertiary age. Instead, regional tilting to the west and strong block faulting along the eastern front of the range accompanied by intrusives were effective during the Late Tertiary.

This Late Tertiary north-south faulting in the San Juancito Mountains and the strong zone of faulting in western Honduras, extending from Puerto Cortez on the Caribbean southward through the Lake Yojoa region to the Gulf of Fonseca on the Pacific, are roughly normal to the axis of the West Indian island arc structural axis. North-south, northeast, and east-west fault systems constitute these north-south trending zones. Volcanic activity is associated with both. The eastern shore line of Nicaragua and the Yucatan peninsula also trend north–south (Fig. 1). This trend may indicate similar zones (Schuchert, 1935, p. 370).

The Central American peninsular area may represent the western fringe of an unstable Caribbean block which reflects the periodic eastward migration of island–arc structure in the Late Paleozoic, Nevadan, Laramide, and, finally, in the late Tertiary. If the Antillean tectogene is as well developed as evidence would indicate (Hess, 1938, p. 87), with related strike-slip movement along the Bartlett Trough fault zone, the intense block faulting and intrusive activity in the San Juancito Mountain region and in other areas of Honduras may be a direct result. In regard to the strike-slip movement along the Bartlett Trough zone, Hess states (p. 88): "Thus it is not inconceivable that Haiti has moved NNE 50 km or more, and once stood below and adjacent to Cuba." Perhaps the Central American peninsula represents a "stretched" portion of the earth's crust developed during the great downwarping in the Antillean region to the east and southeast. Possibly, it is situated over that part of the convection cell in which the drive is upward and eastward toward the tectoclinal zone, assuming that convection is active in the subcrustal.

Among other theories which may explain the development of the structural features of Central America is that advanced by Scheidegger and Wilson (1950, p. 168). They propose shearing in the rigid crust of the earth in the form of thrusting with related normal faulting in the subcrustal as a result of shrinkage on cooling. Both would constitute one system of failure. The structure of the eastern Caribbean on the basis of this theory would be explained as conical failure of the crust in an arcuate pattern with overthrusting to the east and southeast. Again, the Bartlett Trough strike-slip zone would be parallel to the direction of thrusting, and the north-south structures in Central America would be normal to that direction as in the Tectogene theory described above.

Perhaps the coastal or shelf zone of the Pacific fringe of Central America represents a zone of similar overthrusting to the southwest with the active volcanic belt somewhat "inshore" from the zone of failure (Fig. 1). Overthrusting toward the Pacific basin was proposed by Gunn (1947, p. 249) for the Pacific fringe of southern Mexico. If such a zone does exist, the structural development of Central America probably is closely related to it.

Base-metal mineralization with associated silver and gold is concentrated in the southern Cordillera of Honduras (Fig. 1). It extends as a belt westerly from central Nicaragua into Guatemala and crosses the older, northeasterly structural fabric. The mineralization at Rosario is localized at the intersection of the older structural trends and the Late Tertiary north-south zone of faulting and intrusion described above. Mochito, another base-metal and silver producer, is situated immediately west of Lake Yojoa within the Puerto Cortez-Gulf of Fonseca fault zone.

In the opinion of the writer, other such concentrations of mineralization probably have developed within areas of major structural intersection or along strong zones of shearing within this mineral belt particularly where intrusive activity and extensive alteration are evident.

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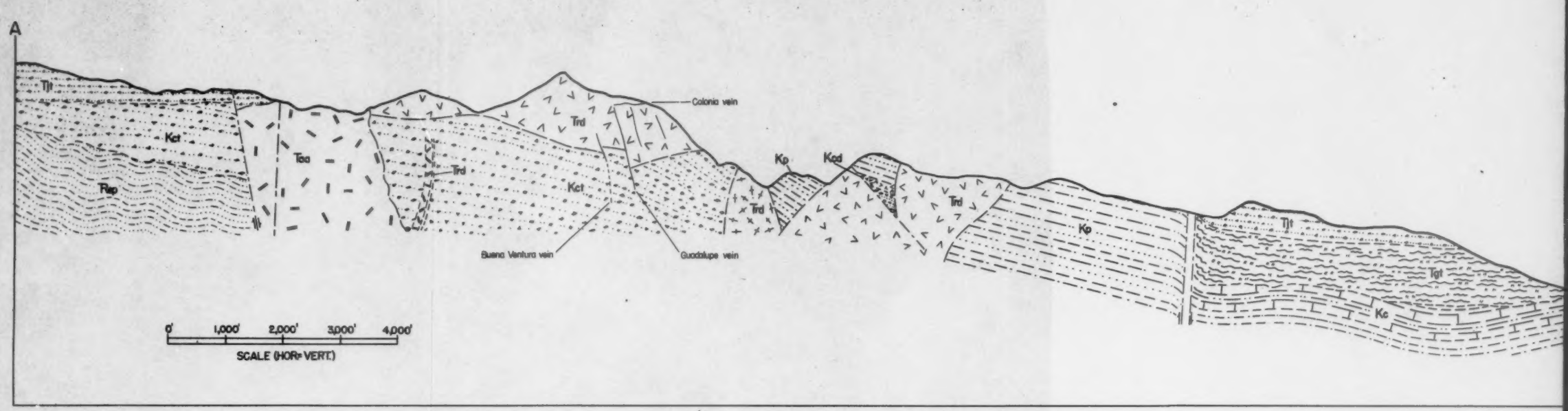
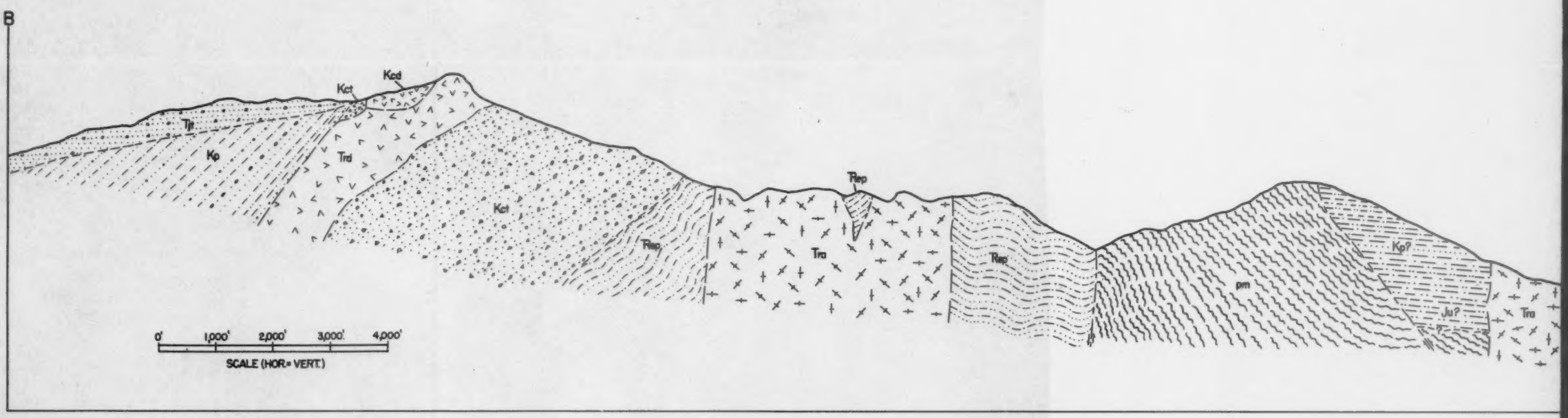




EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

TERTIARY — CRETACEOUS — JURASSIC — UPPER TRIASSIC

- Tjt: Juliapa rhyolitic tuffs and sediments
- Tgt: Guacamayas dacitic tuffs and flows
- Tvf: Valle de Angeles formation
- Kp: Plancitos formation.
- Kcd: Crucero dacitic flows
- Kct: Colonia andesitic tuffs and breccias
- Kc: Cantarranas formation
- Ju: Undefined Jurassic sediments
- Trep: El Plan formati

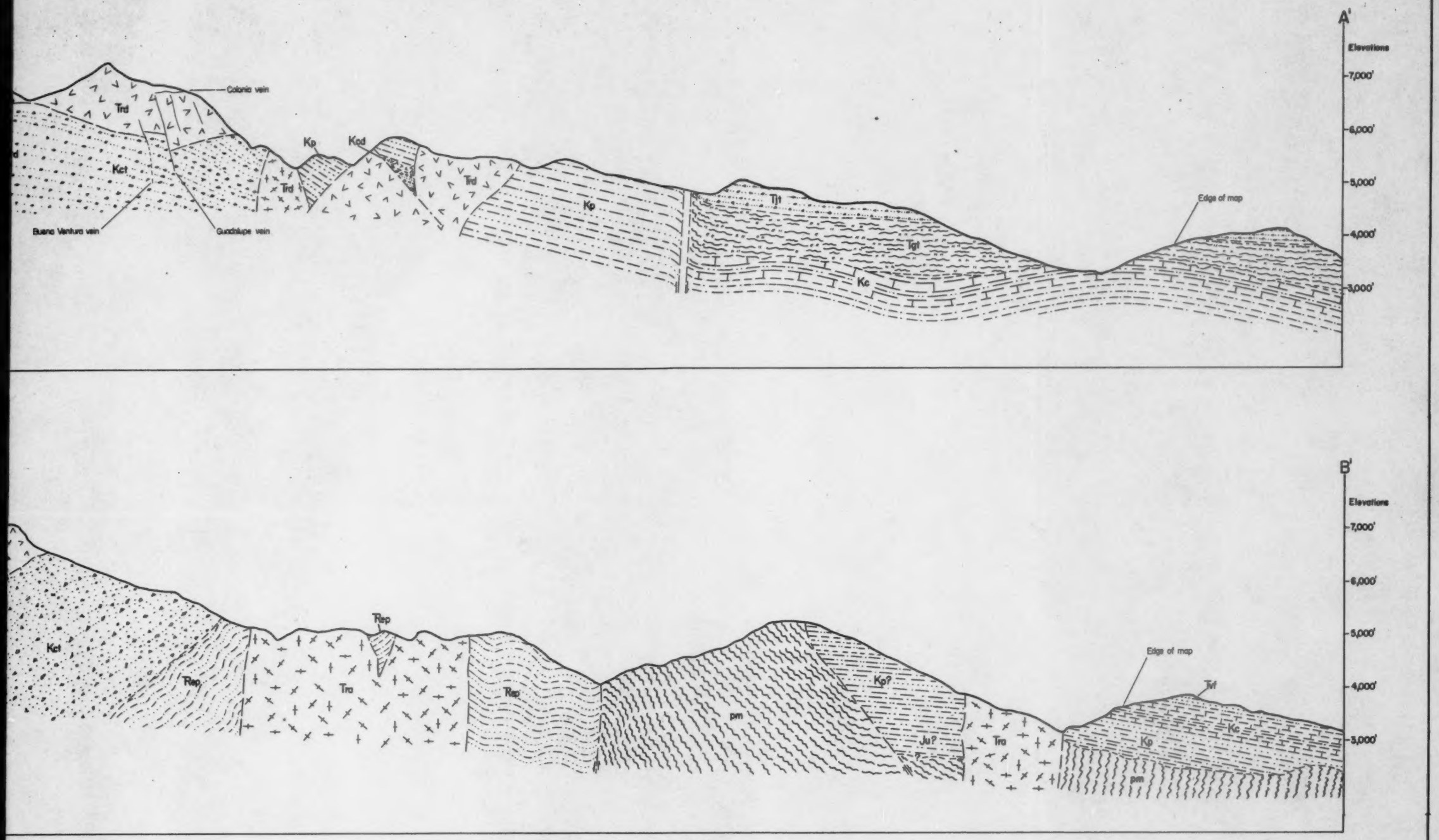
INTRUSIVE IGNEOUS ROCKS

PLIOCENE? — CRETACEOUS?

- Trd: Rancho Quemado dacite
- Tca: Aguacatal porphyritic andesite
- Tra: Reforma hypersthene andesite

Dike — Fault — Contact — Intrusive contact — Vein

NORTH-SOUTH AND EAST-WEST CROSS SECTIONS THROUGH THE CENTRAL SAN JUANCITO MOUNTAINS



EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

CRETACEOUS — JURASSIC — UPPER TRIASSIC — UNKNOWN

Tvf: Valle de Angeles formation

Kp: Plancitos formation.

Kcd: Crucero dacitic flows

Kct: Colonia andesitic tuffs and breccias

Kc: Cantarranas formation

Ju: Undefined Jurassic sediments

Rep: El Plan formation

pm: Peten low-grade metamorphic rocks

INTRUSIVE IGNEOUS ROCKS

PLIOCENE? — CRETACEOUS?

Trd: Rancho Quemado dacite

Tao: Aguacatal porphyritic andesite

Tra: Reforma hypersthene andesite

Dike — Fault — Contact — Intrusive contact — Vein

TH-SOUTH AND EAST-WEST CROSS SECTIONS THROUGH THE CENTRAL SAN JUANCITO MOUNTAINS

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TRACE ELEMENTS OF VOLCANIC ULTRABASIC POTASSIC ROCKS OF SOUTHWESTERN UGANDA AND ADJOINING PART OF THE BELGIAN CONGO

BY RIAD A. HIGAZY

ABSTRACT

The volcanic fields of Southwest Uganda and the adjoining part of the Belgian Congo are characterized by ultrabasic potassic rocks. The principal rock types are katungite, ugandite, and mafurite. Katungite is rich in melilite but free from augite; its potash is mainly in glass. Ugandite and mafurite contain augite, but their dominant feldspathoids are leucite and kalsilite respectively. Olivine is present in these three types. The investigated rocks also include members of the potash ankaratrite-mela-leucitite series, olivine melilitite, kivite or leucite basanite, and limburgite.

The constituents of the pyroclasts include fragments of prevolcanic crustal rocks and a subvolcanic suite of rocks consisting of various combinations of augite, biotite, and olivine. Representatives of both groups occur in the lavas as xenoliths and xenocrysts.

The chemical compositions and trace-element contents of the different types are discussed. They are relatively rich in K_2O, TiO_2, and P_2O_5 and characterized by having $K_2O > Na_2O$ and $Al_2O_3 > (K_2O + Na_2O)$. They possess relatively high abundance of trace elements uncommon in ultrabasic rocks—namely, Sr, Ba, Rb, and Zr.

It is shown that neither the crystallization differentiation nor the limestone-assimilation hypothesis can explain the peculiar geochemical features of the examined rocks. It is suggested that they originated by reactions between carbonatite magma which contributed Ca with Sr, La, and Y; Mg with Cr and Ni; Fe with V and Ti; and P; and sialic crustal rocks which provided Si; Al with Ga; and K with Rb and Ba. The variations in the proportions of the reacting materials and in the physical conditions under which the reactions took place gave rise to differences in the compositions of the various rock types.

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Introduction

Of the many assemblages of alkali igneous rocks described in recent years those of the Toro-Ankole volcanic fields of Southwestern Uganda and the Birunga-Bufumbira or North Kivu field, farther south, are among the most remarkable for their petrographic constitution and the most interesting for their petrogenetic significance. By far the greater part of the work so far accomplished on these rocks has been carried out by the late A. D. Combe in the field in collaboration with Professor A. Holmes in the laboratory. Many rocks from these areas have been analyzed chemically, and samples of the analyzed powders of many of them have been made available to the writer by Professor Holmes for spectrographic determination of the trace elements. This paper deals with the distribution of the trace elements in characteristic rocks from both volcanic fields, and the petrogenetic significance of their unique geochemical features.

The Toro-Ankole fields, east and southeast of Ruwenzori, comprise several areas of tuffs and explosion craters accompanied, in places, by lava flows or near-surface plugs and sheets. Combe collected specimens from:

Katunga, an isolated extinct volcano in the plateau country in the southern portion of the Toro-Ankole province. A general description of Katunga has been given by Combe (1937).

Bunyaruguru, which extends south of Lake George across the Western Rift and adjoining plateau. Combe (1930; 1933; 1939) has described this field. The several explosion craters and lava occurrences of part of this field are shown in a map published by Combe and Holmes (1945, Fig. 2).

Katwe-Kikorongo, an area within the Western Rift, is between Lake Edward and Lake George.

Reference is also made in this paper to the Fort Portal area, farther north. The exact locations of these volcanic areas can be seen in recent editions of the geological map of Uganda and also on maps compiled by Holmes (1950, Fig. 1; 1952, Fig. 1).

The volcanic activity in Toro-Ankole, though now apparently extinct, dates from the Middle Pleistocene to almost the present. The rocks underlying the volcanic products are mainly the Kaiso Series, composed of Pleistocene lacustrine and fluviatile deposits; and Precambrian rocks comprising the post-Karagwe-Ankolean granites, the Karagwe-Ankolean System formed chiefly of argillites, phyllites, and quartzites, and the Toro System composed principally of schists, quartzites, amphibolites, gneisses, and granites.

Except in the Fort Portal area lava flows are very rare; pyroclasts are the dominant products. Katungite, a potassic volcanic rock with abundant olivine and melilite, is the commonest type of lava. It occurs as lava flows only at Katunga, the type locality; elsewhere, it is found almost ubiquitously as bombs, ejected blocks, and lapilli in the agglomerates and tuffs. Each area, however, is distinctive. At Katunga, katungite occurs by itself. In Bunyaruguru there is a greater variety, the two chief additional types being ugandite (a melanocratic olivine-rich leucitite) and mafurite (a rock differing from ugandite in having kalsilite instead of leucite). Mafurite obviously requires a very high K_2O/Na_2O ratio; otherwise potash nepheline appears instead of kalsilite. In the Katwe-Kikorongo area K is generally only a little higher than Na, and consequently the place of mafurite is taken by potash ankaratrite. The latter type is linked to olivine-poor ugandite and mela-leucitite by leucite-ankaratrite, and all rocks of this series are richer in augite than the mafurite-ugandite series of Bunyaruguru.

In the Fort Portal area none of the above types except katungite is present. Lava flows

are abundant, but all are highly altered to calcium carbonate, and only sparse relics of fresh minerals now remain. The original lavas seem to have been nepheline-leucite-melilite types not unlike those of Ninagongo (Birunga) and some of the small volcanoes along the north shores of Lake Kivu.

These unique volcanic rocks and the subvolcanic types, such as biotite pyroxenite, which are invariably associated with them, present unusually difficult problems in petrogenesis. The recent hypothesis advanced by Holmes (1950) to account for the genesis of the most ubiquitous type, katungite, advocates that the latter was produced by reactions between a carbonatite magma and sialic crustal material such as granite and its associates. The magmatic carbonatite is regarded as the source of the cafemic material in the rock, while the sialic material is considered to provide the alk-aluminous constituents and silica. This hypothesis has since been successfully extended to the potash ankaratrite-melaleucitite series of Katwe-Kikorongo (Holmes, 1952).

Bufumbira is the eastern, Uganda part of the very extensive volcanic field of Birunga, which stretches across the Western Rift valley for nearly 50 miles north and northeast of Lake Kivu, for the most part covering regions in the Belgian Ruanda and the Belgian Congo. The positions of its major volcanoes are illustrated by Holmes (Holmes and Harwood, 1937, Fig. 2). The physiography and general geology of this field have been dealt with by Combe (Combe and Simmons, 1933, Chapters I–VI; *see also* the geological map at the end).

Simmons (Combe and Simmons, 1933) gave preliminary petrographic descriptions of the volcanic rocks of Bufumbira. More detailed descriptions, accompanied by chemical analyses and instructive petrological discussions, have been published by Holmes in a valuable series of papers (1936; 1937; 1942; 1945; 1950; 1952; Holmes and Harwood, 1932; 1937; Combe and Holmes, 1945).

Unlike the Toro-Ankole fields, the Birunga-Bufumbira field has many plagioclase-bearing rocks; kivite is the typical leucitic type, and absarokite the potash feldspar-bearing type. In Bufumbira, ugandite is common and links the area to Bunyaruguru. In the south of Birunga nepheline-leucite-melilite rocks characterize Ninagongo and some of the small volcanoes along the north shore of Lake Kivu. This feature recalls the Fort Portal field, except that the Ninagongo rocks are beautifully fresh, whereas those of Fort Portal are heavily carbonated.

It is noteworthy that basalts are absent from both the Toro-Ankole and Birunga-Bufumbira fields, unlike the South Kivu field which is mainly basaltic with associated trachytes and rhyolites.

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He is deeply indebted to Professor Arthur Holmes not only for providing the analyzed powders and for his kindness in placing at my disposal many of his hitherto unpublished chemical analyses, but also for much illuminating discussion and constructive criticism.

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Petrography

General Statement

Holmes' investigations of the volcanic and associated rocks of Toro-Ankole and Birunga include a wealth of information about their detailed petrography, classification, and nomenclature based on their microscopic features and chemical composition. A brief summary of these investigations, with special emphasis on the general petrography of the rocks considered in the present study, may be useful.

The constituents of the pyroclasts include fragments of prevolcanic crustal rocks (accidental) and a subvolcanic (cognate) suite of rocks consisting of various combinations of augite, biotite, and olivine. Representatives of

both groups occur in the lavas—flows, blocks, and lapilli—as xenoliths and xenocrysts.

Accidental Constituents

The accidental xenoliths and xenocrysts and the accompanying ingredients of the tuffs and agglomerates are composed of the underlying crustal rocks, mainly granites, phyllites, and quartzites; and other schists, amphibolites, etc., belonging to the Karagwe-Ankolean and Toro systems. A full list of the varieties of such accidental blocks and xenoliths from Katwe crater has been given by Holmes (Holmes and Harwood, 1932, Table VIII, p. 403). Some of these crustal materials exhibit transfusion phenomena. Specimen K 9, considered in the present investigation, is a partially transfused microcline granodiorite gneiss from Katwe crater. It shows channels consisting of dense buff, glassy or cryptocrystalline material with block inclusions, separating aggregates of granular quartz from large crystals of feldspar. The invading materials are tongues of a pyroxene-rich melilite basalt (Holmes and Harwood, 1932, p. 411–412). Holmes (1936) has also described from Bufumbira several interesting examples of transfused vein quartz or quartzite, accompanied in all cases by marked changes of composition. Moreover, he has demonstrated that granitic xenoliths enclosed in volcanic ejectamenta from Kariya crater (Bunyaruguru) have been transformed during the volcanic activity into leucite, leucitite, and possibly into olivine leucitite (Holmes, 1945).

Cognate Subvolcanic Rocks

The subvolcanic rocks are represented both as ejected blocks in tuffs, agglomerates, etc., and xenoliths in lavas, lapilli, and bombs. These rocks consist essentially of one or more of the minerals olivine, biotite, and pyroxene; for brevity they are conveniently referred to by Holmes (1950, p. 776) as the "O.B.P." series, after the initials of their dominant minerals.

Monomineralic inclusions composed almost entirely of olivine (dunite) occur locally in Bufumbira, but they are too friable to collect (Combe and Simmons, 1933, p. 69).

Monomineralic biotite-bearing rocks (glimmerite) are represented in this study by specimen C 4034a from Kakunyu crater, Bunyaruguru. This rock is composed essentially of biotite with $\gamma = 1.631$, accompanied by no more than traces of augite (Combe and Holmes, 1945, p. 377). Biotite is present in anhedral reddish-brown crystals many of which show distortion, as in the case of glimmerites from other craters (Holmes and Harwood, 1932, p. 406; 1937, p. 31; Combe and Holmes, 1945, p. 376).

The commonest type of pyroxene in the pyroxenites is a pale-green, slightly pleochroic variety of augite with $Z \wedge c = 44°$ and 2V about 60°. Its normative composition in the Kakunyu pyroxenite, C 4035, considered in this study is approximately: diopside, 90 per cent; aegirine, 4; hypersthene, 2; Al_2O_3 and Fe_2O_3, 4 (Combe and Holmes, 1945, p. 375). Many other varieties of augite, some richer in hedenbergite, some in aegirine, and some more titaniferous are also found in the pyroxene-bearing types.

Other rocks of the subvolcanic series are the peridotites (C 1963 and C 4034b) and the biotite pyroxenites (C 2786, G 20, and K 4); the latter are by far the commonest.

C 1963 is a biotite-bearing augite peridotite from an ejected block near Mabungo crater (Bufumbira). Olivine, almost perfectly fresh, forms roughly a quarter of this rock. Augite is more abundant and occurs as prismatic greenish crystals displaying faint pleochroism with X = Z = pale green; Y = yellowish green. Biotite makes up about 8 per cent of the rock, as flakes between the individual crystals of olivine and pyroxene. Its pleochroism is X = green yellow; Y = light brown; Z = brown (Holmes and Harwood, 1937, p. 21–22). The other peridotite (C 4034b), from Kakunyu crater (Bunyaruguru), is richer in biotite and very much poorer in augite. The augite is grayish green; its biotite is reddish brown, with X = very pale yellow; Y = yellowish brown; Z = reddish brown, and is partially corroded marginally. Olivine is found in relatively small fresh grains.

C 2786 is part of an ejected block of biotite-pyroxenite from Lutale crater (Bufumbira). It is a holocrystalline aggregate of copper-colored plates of biotite, blue-black tarnished-looking prisms of augite, and black garnet, with accessory black ores and rare olivine.

Biotite of this type is present in two distinct varieties. The dominant variety displays the pleochroism X = green yellow; Y = light red brown; Z = copper brown; it alternates in the smaller crystals with bands parallel to the cleavage having X = metallic gray; Y = purple gray; Z = deep chestnut brown. The other variety of biotite is less common and invades the dominant type along stripes between the cleavage cracks. Its basal sections resemble melanite and can be readily distinguished from it only by the biaxial interference figure. The garnet of this biotite pyroxenite is a titaniferous melanite found in elongated lobes and aggregates of deep chestnut-brown rounded grains (Holmes and Harwood, 1937, p. 26). Specimen G 20 is a biotite pyroxenite from Katwe crater. Its minerals are similar to those found in other biotite pyroxenites from Katwe described by Holmes (Holmes and Harwood, 1932, p. 408–409). The chief constituents of these rocks are pleochroic diopside-hedenbergite and deep-brown biotite. The accessories are sphene, ilmenite or titaniferous magnetite, melanite, and perovskite, with traces of nepheline. In places, sphene may be present in such conspicuous amounts as to justify naming the rock sphene-rich biotite pyroxenite. Specimen K 4 is a representative of this variety. Holmes points out that in mineralogy and structure the biotite pyroxenites of Southwest Uganda (Holmes and Harwood, 1932, p. 409) closely resemble the corresponding rocks found *in situ* in the Libby stock (Montana) described by Larsen and Pardee (1929).

Leucite kentallenite is an interesting variety of the cognate subvolcanic rocks; so far it has been found only in Birunga, where it is associated with kivite. These rocks differ from the previously mentioned types in possessing feldspars among their constituents. C 3033 is part of an ejected block of leucite kentallenite from the caldera of Nyamuragira, a vigorously active volcano in the western part of Birunga. The rock is composed of phenocrysts of augite and smaller rounded grains of clear brown-green olivine, embedded in a white feldspathic matrix. Augite is purple and displays strong pleochroism with X = fawn, sometimes with a greenish tinge; Y = purple; Z = brownish purple. Zoning is noticeable in some crystals. Leucite and a dominantly feldspathic matrix occupy the interstitial spaces. The matrix is composed of fine-grained plagioclase laths, most of which are zoned (An_{95}–An_{85}), together with smaller amounts of alkali feldspar flecked with yellowish ferruginous staining, biotite in minute flakes, apatite needles, and small grains of olivine (Holmes and Harwood, 1937, p. 113–114).

The specimens of subvolcanic rocks studied in this investigation are as follows:

No. of specimen	Name	Locality	Reference
K 9	Ejected block of partially fused granodiorite-gneiss	Katwe crater, Katwe-Kikorongo	Holmes and Harwood, 1932, p. 411–412
G 20	Ejected block of biotite-pyroxenite	Katwe crater, Katwe-Kikorongo	Holmes and Harwood, 1932, p. 408
K 4	Ejected block of sphene-rich biotite-pyroxenite	Katwe crater, Katwe-Kikorongo	Holmes and Harwood, 1932, p. 409
C 4034a	Xenolith of glimmerite from olivine-rich ugandite	Kakunyu crater, Bunyaruguru	Combe and Holmes, 1945, p. 377
C 4035	Xenolith of pyroxenite from olivine-rich ugandite	Kakunyu crater, Bunyaruguru	Combe and Holmes, 1945, p. 375
C 4034b	Xenolith of biotite-peridotite from olivine-rich ugandite	Kakunyu crater, Bunyaruguru	Combe and Holmes, 1945, p. 377
C 2786	Ejected block of biotite-pyroxenite	Lutale crater, Bufumbira	Holmes and Harwood, 1937, p. 26
C 1963	Ejected block of biotite-bearing augite-peridotite	Mabungo crater, Bufumbira	Holmes and Harwood, 1937, p. 21–22
C 3033	Ejected block of leucite-kentallenite	Caldera of Nyamuragira, Birunga	Holmes and Harwood, 1937, p. 113–114

Volcanic Rocks from Toro-Ankole Fields

The mineralogical classification of the chief volcanic rocks adopted in this study is that introduced by Holmes (1950, Fig. 2, p. 776), shown graphically in (Fig. 1). The principal rock types are katungite, ugandite, and mafurite. Katungite is rich in melilite, but free from augite; its potash is mainly in glass. Ugandite and mafurite contain augite, but their dominant feldspathoids are leucite and kalsilite respectively. Olivine is present in these three types, but there is an important olivine-free variety of katungite which has been given the name proto-katungite (Holmes, 1942, p. 199; 1950, p. 784). The investigated rocks also include members of the potash ankaratrite-melaleucitite series from the Katwe-Kikorongo field. This series differs mineralogically from the ugandite-mafurite series in being conspicuously rich in augite and relatively poor in olivine (Holmes, 1950, p. 776). Xenocrysts derived from the "O.B.P." series differ in the various volcanic rocks. They are mainly, but not exclusively, biotite and augite in the case of katungite; olivine in ugandite; and augite in ankaratrite. Mafurite carries variable amounts of all the three minerals, in many places with a conspicuous abundance of biotite (Holmes, 1950, p. 777).

KATUNGITE: Katungite is the most widely distributed volcanic type. As defined by Holmes (1937, p. 210), who proposed the term, katungite is "an alkali ultrabasic rock with more potash than soda, the essential minerals being melilite and olivine; the potash may be present in glass, zeolites, potash-rich nepheline, kaliophilite [later recognized as a new mineral kalsilite; Holmes, 1942, p. 210], leucite, or biotite; special varieties may be distinguished by appropriate mineralogical prefixes, e.g. leucite-katungite, biotite-katungite, leucite-biotite-katungite."

Its significant characters and relationships to olivine melilitites and related rocks from other regions are discussed in detail by Holmes (1937). The seven katungites investigated include specimens from the Katunga, Bunyaruguru, and Katwe volcanic areas. With one exception (Katunga) they are lapilli or blocks. These specimens are as follows:

No.	Name	Locality	Reference
C 4407	Katungite	W. lava-flow, Katunga	Holmes, 1937, p. 205
G 21	Katungite	Lapilli, Katwe crater	Holmes, 1937, p. 207
G 56	Biotite-katungite*	Ejected block, Katwe crater	Holmes, 1937, p. 207
C 3509	Katungite	Ejected block, Chamakumba crater, Bunyaruguru	Holmes, 1942, p. 212; Combe and Holmes, 1945, p. 367
C 5945	Katungite	Lapilli, NW. edge of Bunyaruguru	Combe and Holmes, 1945, p. 367
C 4012	Kalsilite-katungite	Lapilli, Changabe crater, Bunyaruguru	Holmes, 1942, p. 210; Combe and Holmes, 1945, p. 367
C 6065	Proto-katungite	Ejected block, Lugazi ridge Bunyaruguru	Holmes, 1950, p. 784

* This is an augite-bearing biotite katungite and has been referred to under the more familiar name alnöite (Holmes, 1950, p. 780).

OUACHITITE: The examined specimen (C 5844) is an olivine-rich ouachitite from Katwe crater. It is fine-grained porphyritic rock with phenocrysts of olivine and diopsidic augite. Its groundmass is mainly shreds of reddish-brown biotite and aggregates of diopsidic augite. Associated with these constituents are small olivine crystals and minute grains of perovskite and black ore. Calcite patches and zeolite infillings of vesicles are scattered in the matrix. Rare leucite grains and a few glass-clear crystals of potash nepheline occur interstitially.

Katungite (G 21), augite-bearing biotite-katungite or alnöite (G 56), and ouachitite (C 5844) are all from Katwe crater. They form a series in which there appears to be a com-

plementary relationship between melilite and pyroxene. The katungite is rich in melilite and free from augite, whereas the other end member of the series (ouachitite) has preponderant augite and no melilite. The volume percentages of melilite in these rocks are estimated by Holmes (1950, p. 781) as 37 in katungite, 18 in alnöite, and none in ouachitite.

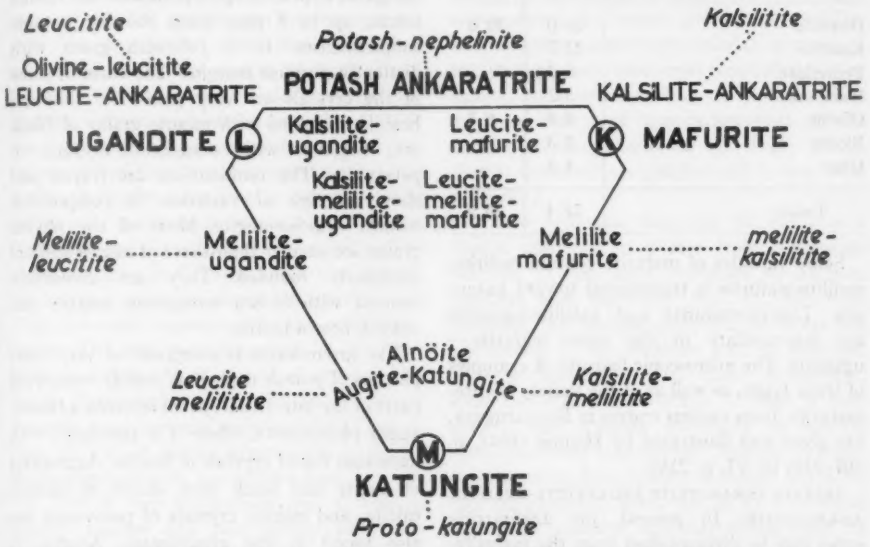

FIGURE 1. TRIANGULAR CLASSIFICATION OF THE ROCK TYPES OCCURRING IN THE VOLCANIC FIELDS NEAR RUWENZORI

L = Leucite and augite; K = Kalsilite and augite; M = Melilite and potash-rich glass, occasionally with kalsilite or leucite. All the types contain olivine, except those in italics. Biotite varieties (including heteromorphs such as olivine ouachitite) of some of the types are known but are not named except in the case of alnöite. The potash ankaratrite series differs from the mafurite-ugandite series in being conspicuously rich in augite and relatively poor in olivine. After Holmes (1950, Fig. 2, p. 776).

UGANDITE: Ugandite was proposed by Holmes (Holmes and Harwood, 1937, p. 11) for melanocratic types of olivine-leucitite. Such volcanic rocks are found in the Katwe-Kikorongo, Bunyaruguru, and Bufumbira volcanic fields. Varieties exceptionally rich in olivine are locally common and are referred to as olivine-rich ugandite.

The ugandite here investigated (C 3052) is an olivine-rich variety from Kichwamba, adjoining Kachuba crater, Bunyaruguru. A detailed petrographic description is given by Holmes (Holmes and Harwood, 1932, p. 414–415). The rock contains conspicuous phenocrysts of olivine, clinoenstatite, and augite. Olivine is sporadically rimmed by biotite. Augite is most generally straw green. Apart from a few small crystals (0.1 to 0.2 mm.) of olivine, augite, and mica, the groundmass is composed of augite microlites, leucite, perovskite, opaque ores, apatite needles, and little patches of calcite and cloudy analcite.

Other interesting varieties of ugandite, are described by Holmes (Combe and Holmes, 1945, p. 371–372) who records nosean in the kalsilite- and kalsilite-melilite-ugandite lavas of Kabirenge and Lyakauli, Bunyaruguru; and also describes Bufumbira ugandites and their relationships to similar volcanic rocks in other provinces (Holmes and Harwood, 1937, p. 60).

MAFURITE: The term mafurite has been proposed by Holmes (1942, p. 199) for olivine mela-kalsilitites, composed of olivine, pyroxene, kalsilite, perovskite, and black ore, found in and around the Mafuru craters, Bunyaruguru. The specimen here investigated (C 6073) is porphyritic, with phenocrysts of deeply corroded olivine and of diopsidic augite. The volume percentages of these and other con-

stituents of the groundmass are given by Holmes (1942, p. 203) as follows:

Groundmass		Phenocrysts
Diopside	26.0	20.6
Kalsilite	23.7	
Perovskite	6.2	
Black ore	5.7	
Olivine	4.4	6.3
Biotite	2.3	
Glass	4.1	
Totals	72.4	26.9

Some varieties of mafurite contain melilite; melilite-mafurite is transitional toward katungite. Leucite-mafurite and kalsilite-ugandite are intermediate in the series mafurite—ugandite. The microscopic features of examples of these types, as well as of the variety biotite-mafurite, from various craters in Bunyaruguru, are given and illustrated by Holmes (1942, p. 207–210; Pl. VI, p. 216).

LEUCITE ANKARATRITE AND LEUCITE-MELILITE ANKARATRITE: In general, the ankaratritic series can be distinguished from the mafurite-ugandite series by its relative abundance of pyroxenes compared with olivine, which may, indeed, be absent from some members (Holmes, 1950, p. 776; 1952). The mineralogical constitution of the Katwe-Kikorongo ankaratrites is closely similar to that of the melanocratic nephelinites of Madagascar, the type ankaratrites described by Lacroix (1923, p. 59). But, on account of their higher potash content and K_2O/Na_2O value, Holmes (Holmes and Harwood, 1932, p. 388) distinguished the Uganda examples by the name "potashankaratrite." By increase of leucite at the expense of potash nepheline these types pass through leucite ankaratrite to mela-leucitite or olivine mela-leucitite, the latter being like olivine-poor ugandite. Melilite-bearing varieties are also known.

The ankaratritic rocks here investigated are leucite ankaratrite (C 5635), from a lava exposed in the wall of Lake Mbuga crater (Holmes, 1952, p. 204), and leucite-melilite ankaratrite (C 5692), part of an ejected block from the south rim of Nyaluzigati crater. Both localities are in the Katwe-Kikorongo field.

C 5635 is a coarse-grained porphyritic variety. The phenocrysts are mainly augite, together with less abundant olivine and some black ores and perovskite. Augite occurs in elongated hypidiomorphic prismatic and bladed forms, up to 8 mm. long, showing notable subparallelism. It is yellowish green with distinctly purplish margins. The cores of some of the crystals are very pale. The rims are heavily sprinkled with minute grains of black ore, together with occasional crystals of perovskite. The terminations are frayed and show no sign of variation in composition toward aegirine-augite. Most of the olivine grains are smaller than those of augite and are irregularly rounded. They are commonly rimmed with brown ferruginous matter and reddish-brown biotite.

The groundmass is composed of very clear patches of potash nepheline, mainly occupying parts of the interstitial spaces between adjacent augite phenocrysts, where it is associated with numerous round crystals of leucite. Aggregates of augite and black ores, shreds of biotite, calcite, and minute crystals of perovskite are also found in the groundmass. Apatite in rounded grains is present as sporadic inclusions in biotite and in the black ores.

Potash ankaratrites and leucite ankaratrites from Mbuga and Nabugando craters in the Katwe-Kikorongo field have recently been described in detail by Holmes (1952). In an earlier paper he gave the modal composition of several rocks belonging to this series (Holmes and Harwood, 1932, p. 387–390, 392–394). The feldspathoidal members in these rocks are potash nepheline with subsidiary leucite, as in the specimen (C 5635) here investigated. Moreover, the mode of C 5635 approximates that of leucite ankaratrite (C 1000) which is as follows (Holmes and Harwood, 1932, p. 387):

Phenocrysts:	
Pyroxenes	50 per cent
Olivine	4
Opaque ores	11
Groundmass:	
Pyroxenes	10
Biotite	4
Ores, etc.	7
Feldspathoids	14

The other investigated ankaratritic rock (C 5692) is a leucite-melilite variety. It is porphyritic, with small phenocrysts of augite and sparse olivine. Augite occurs as yellowish-prismatic crystals arranged in a subparallel manner; purplish margins are lacking, and the rims are not strewn with black ores and perovskite as in the augite phenocrysts of C 5635. Olivine occurs as clear transparent crystals without reaction borders. The groundmass is composed of minute laths of augite, prisms of melilite, cloudy in patches, rounded grains of leucite, occasionally carrying black inclusions, transparent crystals of olivine, black ores, and perovskite, the latter being more abundant than in C 5635. These constituents are set in a greenish glassy background.

MELA-POTASH NEPHELINITE AND MELA-LEUCITITE: The mela-potash nephelinite (C 5566, from an ejected block, north of the Lake in South Nymununka crater, Katwe-Kikorongo volcanic area) and the mela-leucitite (C 5545, from an ejected block, western rim of South Nymununka crater) are olivine free.

C 5566 is very fine-grained, but C 5545 is slightly coarser and porphyritic. They are composed essentially of augite and feldspathoid, as indicated in the names. C 5545 also contains occasional crystals of nosean or hauyne. Together with these constituents, abundant aggregates of black ores and perovskite occur in both rocks. Apatite, occurring as needles, is a minor accessory.

Volcanic Rocks from Birunga Field

The analyzed specimens of the volcanic rocks from the Birunga field are: (1) types with feldspathoids and no feldspars, such as olivine melilitite (C 7360) and potash nepheline melilitite (C 3022); (2) feldspar- and leucite-bearing varieties represented by kivite or leucite basanite (C 3030, C 9780, and C 9892) and leucitic trachybasalt (C 9878); and (3) limburgite (C 7347).

(1) Olivine melilitite (C 7360) comes from Lwabikari crater, north of Lake Kivu, Belgian Congo. It is porphyritic with abundant phenocrysts of augite and occasional olivine. Augite is gray to buff with a purplish tinge and more distinctly purple margins. Some of the larger grains are deeply embayed by the groundmass. Olivine crystals, some of which are corroded, are generally smaller than those of augite. The groundmass is cryptocrystalline and consist mainly of aggregates of black ore and augite, accompanied by small prisms of melilite, olivine grains, glass-clear tabular crystals of potash nepheline, occasional rounded grains of leucite, and small needles of apatite. The mode of this rock approaches that of the melilite-leucite ankaratrite (C 5692) except that it contains less melilite and is free from perovskite.

Potash nepheline melilitite (C 3022) is a typical specimen of a flow from Ninagongo volcano. It has been described by Holmes (Holmes and Harwood, 1937, p. 84), who mentions that melilite-nepheline lavas are not uncommon in the southern part of Birunga, between Ninagongo and Lake Kivu—*e.g.*, from the Bushwaga volcano. C 3022 is fine-grained and consists essentially of melilite laths exhibiting a somewhat trachytic texture, together with clear crystals of potash nepheline and aggregates of black ore, in an interstitial matrix of greenish material which may be chlorophaeite. Perovskite is absent. This rock cannot be matched mineralogically with any of the volcanic types of the Toro-Ankole volcanic areas mentioned above, but it may be akin to the original lavas (now highly carbonated) of the Fort Portal field (Holmes and Harwood, 1932, p. 380).

(2) C 3030 represents a kivite lava, from the northern slopes of Nyamuragira at 9500 feet, which has been described by Holmes (Holmes and Harwood, 1937, p. 116). It is a vesicular porphyritic rock with phenocrysts of purple augite, clusters of plagioclase, and olivine. The groundmass is composed of abundant grains of augite, minute laths of plagioclase, leucite mainly in clear patches, and black ores. Inclusions of leucite kentallenite are present. Holmes describes in detail other kivites from Birunga (Holmes and Harwood, 1937, p. 102–136); and Verhoogen (1948, p. 160) gives the petrographic characters of the lavas of the 1938 Nyamuragira eruption.

C 9780 is a representative of the 1948 eruption of Kituru (a new volcanic cone on the flanks of Nyamuragira). This type is a scori-

aceous and finer-grained variety of kivite but has essentially the same mineralogical constitution as C 3030.

C 9892 represents the 1948 eruption of Muhubuli (a new cone on the same line of fissure as Kituru). The rock is also a kivite, with microscopic features very similar to those of C 9780.

The leucitic trachybasalt C 9878 is from a lava flow erupted in 1948 from a fissure northwest of Kituru. The phenocrysts of this rock are similar to those of the kivites just mentioned, but the groundmass is hyaline except for very minute laths of plagioclase and a few rounded grains of leucite.

(3) C 7347 is a characteristic specimen of the limburgite erupted in 1904 from Nahimbi volcano (formerly called Adolf Friedrich Kegel) situated in the southwestern portion of the Birunga field (Holmes and Harwood, 1937, p. 214). Finckh (1912, p. 20) described the lava as a porphyritic rock with abundant phenocrysts of titanaugite (up to 10 mm) and olivine in a groundmass composed essentially of augite and black ore, together with a little olivine and interstitial brownish glass. The specimen here investigated corresponds, except that the augite is only very faintly purple and the groundmass is much richer in brownish glass.

Analytical Methods and Data Obtained

Samples of the powders originally prepared for chemical analysis of all the above subvolcanic and volcanic rocks were kindly provided by Professor Arthur Holmes for spectrographic investigation.

The trace elements of these rocks, as well as those of four carbonatites (from the Premier Diamond mine, South Africa; Spitzkop alkaline complex, Bushveld, Transvaal; Marongwe Hill, Chilwa Island, Nyasaland; and Hartung, Alnö Island, Sweden), provided by Professor Holmes, Dr. W. Campbell Smith, and Professor H. von Eckermann were spectrographically determined by the author at the Macaulay Institute for Soil Research at Aberdeen, Scotland. The semiquantitative method adopted in this study is that described in detail by Mitchell (1948). The determined elements and the wave lengths of their diagnostic lines have already been listed by the writer (Higazy, 1952a).

Geochemistry of Subvolcanic Rocks (O.B.P.) Series

Major Constituents

The chemical composition and the trace-element contents of the subvolcanic suite of rocks are recorded in Table 1. Three of the chief members of the "O.B.P." series—peridotite, pyroxenite, and glimmerite—are represented by specimens from Kakunyu crater, Bunyaruguru (Nos. 4034b, 4035, and 4034a, respectively).

Of all the major constituents in the three members from Kakunyu crater, the iron oxides have the most uniform distribution, with $FeO > Fe_2O_3$. The range of Fe_2O_3 is from 2.55 per cent in the peridotite to 2.90 in the glimmerite; and that of FeO is confined to the narrow limits of 4.96 per cent in the peridotite to 5.42 in the pyroxenite.

Na_2O is relatively very low and roughly uniform, ranging from 0.26 per cent in the peridotite to 0.56 per cent in the pyroxenite and glimmerite.

The other major constituents, however, show marked variations. As would be expected, Al_2O_3 is low in pyroxenite and peridotite and much higher in glimmerite.

MgO reaches 33.84 per cent in the peridotite, 19.32 in the glimmerite, and 13.14 in the pyroxenite. The difference in the CaO contents of these rocks is still more pronounced. The pyroxenite has 22.57 per cent CaO, whereas the peridotite and the glimmerite have only 2.84 per cent and 1.16 per cent, respectively. The biotite-augite peridotite, C 1963, from Bufumbira, however, possesses lower MgO (19.31 per cent) and considerably higher CaO (16.99 per cent) than the Bunyaruguru peridotite C 4034b. These differences are due to the relative abundance of augite in the Bufumbira peridotite and of olivine in the Bunyaruguru variety.

It is not suprising to find 9.01 per cent K_2O in the glimmerite, since it is composed almost entirely of biotite, which is responsible also for its relatively high TiO_2 (5.18 per cent). The peridotite and the pyroxenite, however,

possess considerably lower K_2O contents—2.58 and 0.08 per cent respectively. The glimmerite and the peridotite have $K_2O > Na_2O$, whereas the pyroxenite has $Na_2O > K_2O$, corresponding to its lack of biotite. All three rock types have $Al_2O_3 > K_2O$.

The analyzed biotite pyroxenites, G 20 from Katwe and C 2786 from Bufumbira, have $K_2O > Na_2O$ and $Fe_2O_3 > FeO$, the reverse of the pyroxenite C 4035. The sphene-rich biotite pyroxenite K 4 of Katwe is remarkable for its very abundant TiO_2 (8.65 per cent) and P_2O_5 (2.80 per cent). Its total FeO and Fe_2O_3 (17.89 per cent) is considerably higher than that of the biotite-pyroxenites of Katwe (9.97 per cent) and Bufumbira (7.91 per cent).

Chemical analysis of the leucite kentallenite (C 3033) from Bufumbira reveals a marked excess of FeO (12.00 per cent) over Fe_2O_3 (1.15 per cent). Since the rock contains plagioclase, Al_2O_3 (12.20 per cent) and Na_2O are higher than in the "O.B.P." series (apart from the high Al_2O_3 of glimmerite).

Thus the subvolcanic rocks show variations in the amounts of their major oxides consistent with their mineralogical constitution. The peridotites (average of C 4034b and C 1963) have $MgO > CaO > (Al_2O_3 + K_2O + Na_2O)$, whereas the pyroxenites (average of G 20, K 4, C 4035, and C 2786) have $CaO > MgO > (Al_2O_3 + K_2O + Na_2O)$; the glimmerite (C 4034a) has $(Al_2O_3 + K_2O + Na_2O) > MgO > CaO$; and the leucite kentalenite (C 3033) has $(Al_2O_3 + K_2O + Na_2O) > CaO > MgO$.

Trace Elements

Rubidium and barium.—The distribution of Rb and Ba in the "O.B.P." subvolcanic types is principally related to that of biotite. The peridotites and the pyroxenite in which biotite is negligible or absent contain less than 1 ppm. of Rb and are relatively poor in Ba (15–50 ppm.). The biotite pyroxenites, however, contain appreciable and almost uniform amounts of Rb (150–170 ppm.). Their Ba contents are relatively high, ranging from 1200 to 2000 ppm. The glimmerite (biotite-rich rock) possesses still higher contents of both Rb (1000 ppm.) and Ba (3200 ppm.). This clearly indicates that, of the ferromagnesian minerals, biotite is the richest depository of these two elements.

The leucite kentallenite is a biotite-free rock, but it contains feldspars, mainly plagioclase, and leucite. The presence of appreciable amounts of Rb (75 ppm.) and Ba (1000 ppm.) in this rock is, therefore, understandable.

The (Rb + Ba) and K_2O contents of the above rocks vary sympathetically, as indicated in the following list:

Type	(Rb + Ba) in ppm.	K_2O in wt. per cent
Pyroxenite	20	0.08
Peridotite (2 analyses)	33	1.73
Leucite-kentallenite	1075	2.02
Sphene-rich biotite-pyroxenite	1370	2.38
Biotite-pyroxenite (2 analyses)	1905	3.55
Glimmerite	4200	9.01

Gallium.—Ga is present in relatively low amounts (<1–10 ppm.) in the peridotites and pyroxenite. The distribution of this element in the other types—namely, biotite pyroxenites, glimmerite, and leucite kentallenite—is almost uniform (20–30 ppm.). The total $(Al_2O_3 + Fe_2O_3)$ in the relatively Ga-poor varieties (5.65–6.86 per cent) is lower than that in the Ga-rich types (11.48–19.42 per cent).

Strontium, lanthanum, and yttrium.—Sr varies from 40 ppm. in the peridotite (C 4034b) to 1000 ppm. in the sphene-rich biotite pyroxenite. The pyroxenite and biotite pyroxenites, which contain little or no sphene, have much less Sr (340–600 ppm.) than the sphene-rich type, indicating that sphene is responsible for the relatively high Sr content of the latter.

The biotite pyroxenites and the glimmerite (rich in biotite) all have Ba > Sr, but the peridotites and the pyroxenite (poor in biotite) have the reverse relationship. The values of Ba/Sr in the biotite pyroxenite (G 20) from Katwe and that from Bufumbira (C 2786) are similar (3.3 and 3.0 respectively). Moreover, the values of the same ratio in the peridotite from Bunyaruguru (C 4034b) and that from Bufumbira (C 1963) are also much the same—0.4 and 0.5 respectively. The pyroxenite (C 4035) shows considerably greater enrichment in Sr relative to Ba; its Sr/Ba value is

16.6. This corresponds to the greater enrichment of Ca relative to K in this rock than in the other types: the CaO/K_2O value is 280 in the pyroxenite (C 4035) and ranges from 1.1 to 19.3 in the biotite pyroxenites and peridotites.

La is present in a detectable amount (<30 ppm.) only in the sphene-rich biotite pyroxenite, which also contains a similar amount of Y. Two of the other rocks also contain Y: the biotite pyroxenite from Katwe (<30 ppm.) and the leucite kentallenite (35 ppm.), although both are free from detectable quantities of La (*i.e.*, much less than 30 ppm.).

Lithium.—Li is present in very low amounts in the different types of the subvolcanic series (<1–8 ppm.). This feature is also noticeable in all the volcanic rocks investigated. The variation of the Li content is so narrow that no significance can be attached to it. Moreover, although Li is liable to be enriched in the micas, it is remarkable that even the glimmerite has <1 ppm. This indicates that the parental materials were deficient in this element. This is confirmed by the analyses of Uganda granites listed by King (1939, Table 3, p. 138); Li_2O is recorded as "none" in seven out of eight analyses and as "trace" in the remaining one.

Chromium, nickel, and cobalt.—The peridotites are characterized by normally high Cr and Ni. The peridotite from Bufumbira has 4000 ppm. Cr and 350 ppm. Ni, and that from Bunyaruguru 2400 ppm. Cr and 1900 ppm. Ni. It is noticeable that the former (relatively rich in pyroxene) has higher Cr and lower Ni contents than the latter (relatively rich in olivine). This supports the writer's statement—in connection with the distribution of these elements in ferromagnesian minerals (Higazy, 1952b)—that the Cr content of the olivines seems to be lower than that of the pyroxenes and that Ni shows the reverse distribution in these two groups.

Cr and Ni are more concentrated in the glimmerite (1500 and 320 ppm. respectively) than in the different varieties of biotite pyroxenite (average: Cr, 775; Ni 190 ppm.) while the pyroxenite has still less (100 and 85 ppm. respectively). The sphene-rich biotite pyroxenite is remarkable in containing negligible amounts of both Cr (<1 ppm.) and Ni (2 ppm.). This rock contains abundant sphene, which forms roughly 40 per cent of its modal composition, together with approximately 60 per cent of yellowish-green pyroxene, biotite, and black ores. The deficiency of this rock in both Cr and Ni is therefore very striking.

The contents of Cr and Ni in the leucite kentallenite are 350 and 120 ppm. respectively, similar to the corresponding averages for gabbros (Cr, 340; Ni, 158 ppm.) as given by Goldschmidt (1937).

The total (Cr + Ni) and the MgO contents of the different types vary rather sympathetically:

Type	(Cr + Ni) in ppm.	MgO in wt. per cent
Peridotite (2 analyses)	4325	26.58
Glimmerite	1820	19.32
Biotite pyroxenite (2 analyses)	965	14.72
Pyroxenite	185	13.14
Sphene-rich biotite pyroxenite	2	7.53

The distribution of Co is much less variable than that of Cr and Ni; the average contents of the various types fall within the range 55 to 75 ppm.

All the varieties except the sphene-rich biotite pyroxenite are characterized by Cr > Ni > Co, as in ordinary ultrabasic rocks (Lundegårdh, 1949; Higazy, 1952b). The sphene-rich biotite pyroxenite, however, has Co > Ni > Cr.

Vanadium and copper.—On the whole, the pyroxenites contain more V than the other members of the "O.B.P." series. The sphene-rich biotite pyroxenite has the highest content of this element (550 ppm.); the biotite pyroxenites (345 ppm.) and the glimmerite (200 ppm.) come next, followed by pyroxenite (150 ppm.) and the peridotites (120 ppm.). V can be present in pyroxenes, sphene, and biotite. V^3 (ionic radius, 0.65 Å) replaces Fe^3 (0.67) in the pyroxene structure. But in the sphene and biotite lattices, V is most likely to be present in its tetravalent state replacing Ti^4, since V^4 and Ti^4 have similar ionic radii, 0.61 and 0.64 Å respectively. The concentration of V in the leucite kentallenite (380 ppm.) is approximately the same as that of the average content in the pyroxenites (350 ppm.).

The total (Co + V) in the different types increases with increase in the total (FeO + Fe_2O_3) as follows:

Type	(Co + V) in ppm.	(FeO + Fe_2O_3) in wt. per cent
Peridotite (2 analyses)	188	6.57
Pyroxenite	205	8.03
Glimmerite	255	8.14
Biotite pyroxenite (2 analyses)	408	8.94
Leucite kentallenite	455	13.15
Sphene-rich biotite pyroxenite	610	17.89

The Cu content of the biotite pyroxenites (average 75 ppm.) is higher than that of the peridotites (average 45 ppm.). But the glimmerite and pyroxenite both contain only 3 ppm. of this element. The distribution of Cu is obviously very erratic in these rocks.

The total (Cr + Ni + Co + V + Cu) increases with the total (MgO + FeO + Fe_2O_3) as follows:

Type	(Cr+Ni+Co+V+Cu) in ppm.	(MgO+FeO+Fe_2O_3) in wt. per cent
Pyroxenite	393	21.17
Leucite kentallenite	960	23.41
Biotite pyroxenite (2 analyses)	1448	23.91
Glimmerite	2078	27.46
Peridotite (2 analyses)	4558	33.15

These trace elements are known to replace Mg, Fe^2 and Fe^3 in appropriate crystal lattices.

Other trace elements.—Zr is much more abundant in the sphene-rich biotite pyroxenite (1200 ppm.) than in the other types (<10–250 ppm.). This indicates that the sphene in this rock is relatively rich in Zr.

Sc is found in detectable amounts (15–40 ppm.) only in the pyroxene-rich rocks; its content in augite-poor peridotite, glimmerite, and leucite kentallenite is below the limit of sensitivity (<10 ppm.).

Ag is detectable, except in the leucite kentallenite, since all the members of the "O.B.P." series have variable amounts of this element ranging from 1 to 20 ppm.

The variation in the distribution of Pb cannot be determined. Most of the examined types have <10 ppm. of this element.

Mo is detectable only in the peridotites (average, 2 ppm.) while Be and In are determinable only in the glimmerite (5 and <10 ppm. respectively). Tl and Ge, if present, are in amounts below the limits of sensitivity.

Summary

Generally, the outstanding features of the distribution of the trace elements in the analyzed members of the "O.B.P." series are as follows:

(1) Cr and Ni are relatively abundant in the peridotites; Rb and Ba in the glimmerite; and Sr and (Co + V) in the biotite pyroxenites.

(2) Li is very sparse in all the members.

(3) All the types except sphene-rich biotite pyrosenite have Cr > Ni > Co as in normal ultrabasic rocks.

(4) The average peridotite has MgO > CaO > (Al_2O_3 + K_2O + Na_2O), while the glimmerite has (Al_2O_3 + K_2O + Na_2O) > MgO > CaO. Correspondingly the former shows (Cr + Ni) > (Sr + La + Y) > (Ga + Rb + Ba), and the latter has (Ga + Rb + Ba) > (Cr + Ni) > (Sr + La + Y). The pyroxenite has CaO > MgO > (Al_2O_3 + K_2O + Na_2O) and accordingly shows (Ga + Rb + Ba) > (Sr + La + Y) > (Cr + Ni).

(5) The biotite pyroxenites have MgO > CaO > (Al_2O_3 + K_2O + Na_2O) and (Ga + Rb + Ba) > (Cr + Ni) > (Sr + La + Y); and the sphene-rich biotite pyroxenite has CaO > (Al_2O_3 + K_2O + Na_2O) > MgO and (Ga + Rb + Ba) > (Sr + La + Y) > (Cr + Ni).

(6) The leucite kentallenite is characterized by relatively moderate amounts of Rb, Ba; Sr; and Cr and Ni. It has Cr > Ni > Co; and (Ga + Rb + Ba) > (Sr + La + Y) > (Cr + Ni) corresponding to the relation (Al_2O_3 + K_2O + Na_2O) > CaO > MgO.

Geochemistry of Volcanic Rocks

Katungite, Ugandite, and Mafurite

Major constituents.—The chemical compositions of the investigated katungites, ugandite,

and mafurite are recorded in Table 2. The katungites of the different volcanic areas vary but little in the contents of their major oxides, and consequently no individual katungite differs significantly from the average composition here adopted for discussion. Certain characters are shared by all three types. All are relatively rich in K_2O (3.46–6.98 per cent) and TiO_2 (3.52–4.86) and have $K_2O > Na_2O$; their chief feldspathoids are leucite and/or kalsilite. They also have $Al_2O_3 > (K_2O + Na_2O)$, thus differing from the leucite-bearing rocks of West Kimberley, Western Australia, which have $K_2O > Al_2O_3$ (Wade and Prider, 1940).

The chief mineralogical differences are naturally reflected chemically. Katungite, being melilite-rich, possesses the highest CaO content (16.06 per cent). Ugandite, being the richest in olivine, has the highest MgO (24.84 per cent). Mafurite, being kalsilite-rich, contains the highest Al_2O_3 (8.18 per cent) and K_2O (6.98 per cent).

Average katungite possesses higher CO_2 (1.53 per cent) and P_2O_5 (0.97 per cent) than mafurite (trace and 0.61 per cent respectively) and ugandite (0.36 per cent and 0.29 per cent respectively).

Among the members of the "O.B.P." series, the average composition of biotite pyroxenite has features in common with average katungite, just as the peridotites have with olivine-rich ugandite. Glimmerite similarly shares certain chemical features with mafurite.

Trace elements.—The trace-element contents of the three volcanic types are given in Table 2. The variations in the katungites from the different volcanic areas are insignificant. Proto-katungite, however, has notably more Ba, Sr, La, and Cu, and less Cr, Ni, and V than average katungite.

RUBIDIUM AND BARIUM: Generally, the three main volcanic types have abundant Rb, which is most likely replacing K in leucite and/or kalsilite, or accompanying it in the potash-rich groundmass. Both ugandite (relatively rich in leucite) and mafurite (relatively rich in kalsilite) have 450 ppm. of Rb, whereas the average katungite (containing potash-rich glass and generally poor in leucite and/or kalsilite) has 220 ppm. Kasilite katungite from Bunyaruguru has more Rb (380 ppm.) than three other kalsilite-free katungites from the same field (150–240 ppm.).

The volcanic rocks of Southwest Uganda are highly enriched in Ba, as was first reported by Holmes and Harwood (1932, p. 420). Ba reaches 7500 ppm. in the K_2O-rich mafurite, compared with 3370 ppm. in katungite and 2000 ppm. in ugandite. In mafurite and ugandite, Ba appears to be chiefly present replacing K in their feldspathoids. The relatively high Ba content of katungite suggests that this element may in part replace Ca in melilite. This view is strengthened by the fact that uncompahgrite (a coarse-grained melilite-pyroxene rock occurring at Iron Hill, Gunnison County, Colorado) has 2685 ppm. of Ba, whereas ijolite (melilite-free) from the same locality has only 895 ppm. (Larsen, 1942, p. 36). The possibility, however, that Ba chiefly exists among the constituents of the potash-rich groundmass of katungite cannot be overlooked.

STRONTIUM: The volcanic rocks of Southwestern Uganda are also remarkable for their abundant Sr. Katungite and mafurite have similar amounts, 6685 and 7000 ppm. respectively, but ugandite, corresponding to its relatively low Ca, has a much lower content (1800 ppm.).

The Sr contents of both mafurite and ugandite are slightly lower than those of Ba; whereas katungite has considerably more Sr than Ba. This is understandable, since katungite is rich in melilite, the mineral in which most of the Sr, replacing Ca, is likely to exist. That Sr is more easily accommodated into the melilite lattice than into that of pyroxene becomes very obvious when we consider that pyroxenite (C 4035, Table 1; pyroxene-rich and melilite-free) has 22.57 per cent CaO and possesses only 340 ppm. Sr; whereas katungite (C 4012, Table 2; pyroxene-free and melilite-rich) has only 16.79 per cent CaO and possesses as much as 9500 ppm. Sr.

LANTHANUM AND YTTRIUM: The volcanic types contain both La and Y in detectable amounts, with La > Y. The variation of La in the different katungite samples is from 30 to 70 ppm., but proto-katungite has more abundant La (100 ppm.) in accordance with the corresponding relative abundance of Sr. Mafurite and ugandite have 80 and 35 ppm. of La respectively. The Y content of the three

TABLE 1.—CHEMICAL COMPOSITION AND TRACE ELEMENT CONTENTS OF MEMBERS OF THE SUBVOLCANIC SERIES

Chemical Analyses

	A C4034b	B C1963	C C4035	D K4	E G20	F C2786	G C4034a	H C3033
SiO_2	42.59	47.33	50.39	33.99	44.39	43.35	38.18	42.91
Al_2O_3	3.82	6.84	3.04	5.86	6.37	9.67	16.52	12.20
Fe_2O_3	2.55	0.02	2.61	9.35	5.11	5.26	2.90	1.15
FeO	4.96	5.62	5.42	8.54	4.86	2.65	5.24	12.00
MnO	0.10	0.12	0.05	0.15	0.10	0.09	tr.	0.19
MgO	33.84	19.31	13.14	7.53	14.20	15.74	19.32	10.26
CaO	2.84	16.99	22.57	18.23	17.02	12.20	1.16	13.65
Na_2O	0.26	0.41	0.56	0.69	0.50	0.44	0.56	1.60
K_2O	2.58	0.88	0.08	2.38	2.35	4.74	9.01	2.02
H_2O^+	2.96	0.55	0.14	0.96	0.35	0.59	1.22	0.20
H_2O^-	0.63	0.21	none	0.18	0.05	0.07	0.58	0.02
CO_2	0.25	0.02	none	0.30	0.04	0.04	none	0.06
TiO_2	1.60	1.26	1.96	8.65	3.91	4.38	5.18	3.37
P_2O_5	0.22	0.21	tr.	2.80	0.26	tr.	.....	0.36
Cl	0.05	tr.	.....	0.02	0.04	tr.	.....	0.08
F	0.12	0.01	.....	0.09	0.04	0.11	.....	0.06
S	0.18	0.01	.....	0.03	0.02	tr.	.....	0.05
Cr_2O_3	0.23	0.32	.....	none	0.03	0.05	0.14	0.02
V_2O_3	0.01	0.04	.....	0.07	0.05	0.04	.....	0.06
NiO	0.21	0.04	.....	none	0.01	0.04	.....	0.01
BaO	0.13	0.03	tr.	0.13	0.16	0.30	0.16	0.05
SrO	0.02	none	0.12	0.05	0.03	none	0.22	0.05
Li_2O	tr.	tr.	.....	none	tr.	tr.	.....	.....
CuO	.....	.....	.....	.....	.....	0.03	.....	0.05
Total	100.15	100.22	100.08	100.00	99.89	99.79	100.39	100.42
Less O	0.11	0.01	.....	0.05	0.03	0.04	.....	0.04
	100.04	100.21	100.08	99.95	99.86	99.75	100.39	100.38

Trace-Element Contents

(ppm.)

Rb	1	*	*	*	170	160	150	1000	75
Li	1	2	4	6	3	1	1	*	8
Ba	5	15	50	20	1200	2000	1500	3200	1000
Sr	5	40	100	340	1000	600	500	240	1000
Cr	1	2400	4000	100	*	900	650	1500	350
Co	2	45	90	55	60	75	50	55	75
Ni	2	1900	350	85	2	150	230	320	120
Zr	10	40	90	200	1200	50	70	*	250
La	30	*	*	*	<30	*	*	*	*
Y	30	*	*	*	<30	<30	*	*	35
Cu	3	40	50	3	50	90	60	3	35

TABLE 1.—Continued

Element	Sensitivity	A	B	C	D	E	F	G	H
V	5	110	130	150	550	400	290	200	380
Ga	1	*	5	10	30	25	20	25	20
Tl	30	*	*	*	*	*	*	*	*
Sn	5	5	10?	*	*	*	*	<5	*
Pb	10	<10	<10	<10	<10	<10	<10	10	<10
Sc	10	*	20?	40	*	20	15	*	*
Mo	1	3	1	*	*	*	*	*	*
Ge	10	*	*	*	*	*	*	*	*
Be	5	*	*	*	*	*	*	5	*
Ag	1	2	3	15	5	20	1	1	*
In	10	*	*	*	*	*	*	<10?	*

Analyst: R. A. Higazy (spectrographic)
* = Considerably less than the respective limits of sensitivity
A = Biotite peridotite. Xenolith from ejected block of olivine-rich ugandite, C 4034b, Kakunyu crater, Bunyaruguru (Combe and Holmes, 1945, p. 377), Analyst: H. F. Harwood
B = Biotite-bearing augite peridotite. Ejected block, C 1963, Mabungo crater, Bufumbira (Holmes and Harwood, 1937, p. 23). Analyst: H. F. Harwood
C = Pyroxenite. Xenolith from ejected block of olivine-rich ugandite, C 4035, Kakunyu crater, Bunyaruguru (Combe and Holmes, 1945, p. 377). Analyst: W. H. Herdsman
D = Sphene-rich biotite pyroxenite. Ejected block, K 4, Katwe crater (Holmes and Harwood, 1937, p. 30). Analyst: H. F. Harwood
E = Biotite pyroxenite. Ejected block, G 20, Katwe crater (Holmes and Harwood, 1937, p. 30). Analyst: H. F. Harwood
F = Biotite pyroxenite. Ejected block, C 2786, vent on S.S.W. and of Lutale Ridge, Bufumbira (Holmes and Harwood, 1937, p. 29). Analyst: H. F. Harwood
G = Glimmerite. Xenolith from ejected block of olivine-rich ugandite, C 4034a, Kakunyu crater, Bunyaruguru (Combe and Holmes, 1945, p. 377). Analyst: W. H. Herdsman
H = Leucite kentallenite. Ejected block, C 3033, Nyamuragira, Belgian Congo. New analysis by Imperial Chemical Industries Limited, Research Department, Billingham, Co. Durham

types appears to be similar (<30 ppm.), but there may be undetectable differences in the concentration of this element since its sensitivity is 30 ppm.

Compared with the subvolcanic rocks (as in the case of Sr) the volcanic types are richer in both La and Y.

GALLIUM: The Ga contents of katungites from the different volcanic areas (Katwe-Kikorongo, Bunyaruguru, and Katunga) are almost uniform (20–30 ppm.) with an average of 25 ppm. Mafurite and ugandite have 15 and 5 ppm. of this element respectively. The increase of Ga with (Al_2O_3 + Fe_2O_3) which characterizes the subvolcanic series, is again found in the chief volcanic types:

Type	Ga in ppm.	(Al_2O_3 + Fe_2O_3) in wt. per cent
Ugandite	5	9.41
Mafurite	15	12.79
Katungite	25	14.83

LITHIUM: Li is present in uniform and relatively low amounts in the three types (5 to 8 ppm.).

CHROMIUM, NICKEL, AND COBALT: Cr and Ni are relatively high in the three volcanic types, all of which are rich in olivine. Ugandite and mafurite have 1200 and 900, and 1300 and 300 ppm. respectively, while katungite averages only 720 and 185 ppm., and proto-katungite has even less: 290 and 100 ppm.

The increase of (Cr + Ni) with MgO that characterizes the subvolcanic series is again found in the volcanic rocks as follows:

Type	(Cr + Ni) in ppm.	MgO in wt. per cent
Proto katungite	390	10.93
Katungite	905	12.40
Mafurite	1600	17.66
Ugandite	2100	24.84

The contents of Co in katungite, mafurite, and ugandite are 73, 70, and 110 ppm. re-

spectively. Similarly, the FeO contents of both katungite and mafurite are almost alike (5.06 and 4.98 per cent respectively), but that of ugandite is higher (6.47 per cent).

All the types have Cr > Ni > Co, as in the subvolcanic series.

VANADIUM: V appears to increase with (Fe_2O_3 + TiO_2):

Type	V in ppm.	(Fe_2O_3 + TiO_2) in wt. per cent
Ugandite	110	7.55
Mafurite	220	8.97
Katungite	275	11.99

The total of the trace elements known to replace Mg, Fe^2, and Fe^3 in the crystal lattices namely, Cr, Ni, Co, V and Cu, increases with the total of these major elements:

Type	(Cr + Ni + Co + V + Cu) in ppm.	(MgO + FeO + Fe_2O_3) in wt. per cent
Katungite	1238	23.59
Mafurite	1915	27.25
Ugandite	2380	35.34

Comparison of these constituents with those of the subvolcanic rocks shows that the corresponding totals for katungite and mafurite are closely similar to those for biotite pyroxenite and glimmerite respectively. Furthermore, for both ugandite and peridotite these totals are higher. But ugandite has slightly higher (MgO + FeO + Fe_2O_3) and lower (Cr + Ni + Co + V + Cu) totals (35.34 per cent and 2380 ppm.) than those of peridotite (33.15 per cent and 4558 ppm.).

ZIRCONIUM: The distribution of Zr is very interesting. While both katungite and mafurite have relatively high contents of this element (1000 and 900 ppm. respectively), ugandite possesses only 300 ppm. Among the members of the "O.B.P." series, the sphene-rich biotite pyroxenite has an enormous quantity of Zr (1200 ppm.), most of which is present in sphene. Neither katungite nor mafurite carries sphene, but they have appreciable amounts of perovskite. It is quite likely, therefore, that most of the Zr in these rocks is present in this mineral, replacing Ti^4.

It is highly significant that in all three types Zr is extraordinarily abundant as compared with normal ultrabasic rocks. Rankama and Sahama (1950, p. 566) report 60 ppm. as the average Zr content of peridotite. Moreover, three ultrabasic rocks from Garabal Hill-Glen Fyne complex, Scotland—dunite, augite peridotite, and pyroxenite—have <10 ppm. of this element (Nockolds and Mitchell, 1948, Table II, analyses 1, 2, 3, p. 538).

OTHER TRACE ELEMENTS: Pb is present in amounts less than 10 ppm. in all three types; and differences are therefore undetectable since the sensitivity is 10 ppm.

Tl, Sn, Sc, Mo, Ge, Be, Ag, and In, if present, occur in amounts below their respective limits of sensitivity in these volcanic rocks.

Summary.—The outstanding features of katungite, mafurite, and ugandite are:

(1) Elements uncommon in ultrabasic rocks—namely, Sr, Ba, Rb, and Zr—are very abundant.

(2) Elements common in ultrabasic rocks—namely, Cr and Ni—are normally abundant.

(3) (Sr + La + Y) increases with Ca; (Rb + Ba) with K and (Cr + Ni) with Mg.

(4) All three rocks have Cr > Ni > Co. Mafurite and ugandite have Ba > Sr, whereas katungite has Sr > Ba.

(5) Sr and Ba are notably more abundant than in the members of the "O.B.P." series. Otherwise, the trace-element abundances are generally similar for katungite and biotite pyroxenite; mafurite and glimmerite; and ugandite and peridotite.

Ouachitite

The chemical composition of ouachitite (Table 2) has much in common with katungite (Table 2) and biotite pyroxenite (Table 1).

The noteworthy features of the trace-element abundances of ouachitite (Table 2) are:

(1) Ba and Sr are both lower than in katungite, but the relation Sr > Ba remains the same, whereas biotite pyroxenite has Ba > Sr.

(2) Both Sr and Zr are conspicuously abundant compared with the corresponding amounts in biotite pyroxenite. Zr is also somewhat higher than in katungite.

It is noticeable that the Sr content decreases from proto-katungite (>10,000 ppm.), through katungite (6685 ppm.), alnöite (3800 ppm.),

Element	A	B	C	D	E	Average A and E	Average B, C and D
Rb	240	200	150	100	155	198	150
Ba	7000	2800	2600	1700	1725	4360	2100
Sr	>10,000	7500	3800	2500	550	5300	4600
Cr	290	700	800	550	775	533	683
Co	60	85	70	60	62	61	72
Ni	100	230	140	250	190	145	207
Zr	1100	800	1100	1200	60	580	1030
La	100	30	<30	<30	*	50	<30
Y	<30	<30	<30	<30	<30	<30	<30
Cu	200	80	60	65	75	138	68
V	170	320	350	320	345	260	330
Ga	25	25	30	25	23	24	27

A, Proto-katungite C 6065, Bunyaruguru
B, Katungite G 21, Katwe
C, Alnöite (biotite-augite katungite) G 56, Katwe
D, Ouachitite C 5844, Katwe
E, Average of biotite pyroxenites G 20, Katwe and C 2786, Bufumbira
* Considerably less than 30 ppm.

ouachitite (2500 ppm.) to biotite pyroxenite (550 ppm.). Ba and Rb show also a decrease from proto-katungite to ouachitite. As shown in the above tabulation, the average trace-element contents of the end members of the series (proto-katungite and biotite pyroxenite) are not very different from the corresponding averages for katungite, alnöite, and ouachitite.

Other Volcanic Rocks from Toro-Ankole Volcanic Province

General remarks.—The remaining rocks investigated from the Toro-Ankole volcanic province all come from the Katwe-Kikorongo field. They comprise potassic ankaratritic types, mela-potash nephelinite, and mela-leucitite. The chemical composition and the trace-element contents of these rocks are given in Table 3.

Potassic ankaratritic rocks.—In general, the analyzed leucite ankaratrite and leucite-melilite ankaratrite have many chemical characteristics in common with katungite, mafurite, and ugandite (K.M.U.)—*e.g.*, relatively high K_2O and TiO_2, with $K_2O > Na_2O$ and $Al_2O_3 > (K_2O + Na_2O)$. The ankaratritic types, however, have certain systematic geochemical differences corresponding to their greater abundance of augite relative to olivine: notably lower MgO; higher Al_2O_3 and Na_2O; and $(FeO + Fe_2O_3) > MgO$, the latter being the reverse of what has been found in the "K.M.U." series. These differences justify the recognition of the ankaratritic types as a distinctive group.

Comparison of the trace-element contents of the leucite ankaratrite with those of the leucite melilite ankaratrite (Table 3, Columns A and B) reveals these interesting features:

(1) Cr and Ni are very similar in both varieties, corresponding to their similar MgO contents.

(2) V is noticeably higher in the leucite melilite ankaratrite, where perovskite and TiO_2 are more abundant.

(3) The leucite ankaratrite has more CaO (16.59 per cent) than the leucite-melilite ankaratrite (14.34 per cent). Yet, Sr is notably lower in the melilite-free variety (4000 ppm.) than in the melilite-rich type (9800 ppm.). This is another example illustrating the relative enrichment of melilite-bearing rocks in Sr.

(4) Rb and Ba are more abundant in the leucite-melilite ankaratrite, corresponding to its higher K_2O content.

The average value of (Cr + Ni) is lower than that for any of the "K.M.U." series, corresponding to the lower MgO of the ankaratritic rocks. On the other hand, (V + Co) and Ga are higher, corresponding to the higher values of $(FeO + Fe_2O_3 + TiO_2)$ and $(Al_2O_3 + Fe_2O_3)$

TABLE 2.—CHEMICAL COMPOSITION AND TRACE-ELEMENT CONTENTS OF KATUNGITE, MAFURITE, UGANDITE, AND OUACHITITE

	Katungites							Average Katungite	Mafurite	Ugandite	Ouachitite
	Katwe-Kikorongo		Bunyaruguru				Katunga				
	A	B	C	D	E	F	G		H	I	J
Chemical Analyses											
SiO_2	35.51	37.93	33.89	34.23	33.22	33.52	35.37	35.09	39.06	40.47	38.94
Al_2O_3	6.83	6.59	8.27	8.02	9.71	8.04	6.50	7.70	8.18	5.38	6.92
Fe_2O_3	9.68	6.81	7.03	6.62	6.68	5.88	7.23	7.13	4.61	4.03	5.27
FeO	2.70	4.37	5.21	5.34	5.30	5.50	5.00	5.06	4.98	6.47	5.09
MnO	0.22	0.18	0.26	0.22	0.52	0.15	0.24	0.26	0.26	0.23	0.23
MgO	11.67	14.54	10.93	9.92	12.12	13.54	14.08	12.40	17.66	24.84	11.58
CaO	16.00	15.23	16.98	16.54	15.64	15.22	16.79	16.06	10.40	8.06	15.95
Na_2O	1.56	0.88	1.42	1.20	1.51	1.42	1.32	1.33	0.18	0.68	1.01
K_2O	3.30	2.65	3.65	3.39	3.54	4.26	4.09	3.56	6.98	3.46	3.96
H_2O^+	3.11	3.38	2.08	2.80	3.28	2.34	2.78	2.82	1.42	1.11	2.26
H_2O^-	1.31	1.42	1.19	1.72	0.80	1.68	1.15	1.32	0.50	0.57	1.20
CO_2	1.47	0.50	3.27	4.02	0.42	0.96	0.09	1.53	tr.	0.36	2.12
TiO_2	4.88	4.12	4.43	4.56	6.08	6.04	3.87	4.86	4.36	3.52	3.88
P_2O_5	1.18	1.03	0.97	0.96	1.12	0.82	0.74	0.97	0.61	0.29	0.91
Cl	tr.	0.01	...	...	...	...	0.02	...	...	0.01	...
F	0.27	0.16	0.18	0.14	0.08	...	0.16	...	0.13	0.10	0.13
S	...	...	0.14	0.12	...	...	0.35	...	0.13	0.04	0.14
SO_3	0.13	0.06	...	...	...	...	...	...	...	...	...
Cr_2O_3	0.02	0.05	...	...	...	...	0.01	...	0.08	0.11	...
V_2O_3	0.04	0.02	...	...	...	...	0.03	...	...	0.03	...
NiO	0.02	0.03	...	...	...	...	0.19	...	tr.	0.13	0.09
BaO	0.27	0.30	0.21	0.20	0.17	0.15	0.25	...	0.32	0.27	0.18
SrO	0.24	0.25	0.29	0.23	0.05	0.44	0.04	...	0.18	0.02	0.19
Li_2O	tr.	...	...	...	...	...	none	...	...	...	...
CuO	...	...	...	...	...	...	0.06	...	...	...	...
Total	100.41	100.51	100.40	100.23	100.24	99.96	100.36	100.09	100.04	100.18	100.05
Less O	0.11	0.07	0.11	0.11	0.03	...	0.24	...	0.10	0.05	0.09
	100.30	100.44	100.29	100.12	100.21	99.96	100.12	100.09	99.94	100.13	99.96
Trace-Element Contents (ppm.)											
Rb	200	150	240	220	150	380	200	220	450	450	100
Li	10	12	8	7	6	6	8	8	5	7	13
Ba	2800	2600	7000	2000	1800	4500	2900	3370	7500	2000	1700
Sr	7500	3800	>1%	7500	4000	9500	4500	6685	7000	1800	2500
Cr	700	800	290	650	500	1200	900	720	1300	1200	550
Co	85	70	60	80	80	70	65	73	70	110	60
Ni	230	140	100	200	160	180	270	185	300	900	250
Zr	800	1100	1100	850	1200	800	1200	1000	900	300	1200
La	30	<30	100	50	30	70	40	50	80	35	<30
Y	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Cu	80	60	200	70	60	50	70	85	25	60	65
V	320	350	170	260	350	210	250	275	220	110	320

TABLE 2.—Continued

	Katungites							Average Katungite	Mafurite	Ugandite	Ouachitite
	Katwe-Kikorongo		Bunyaruguru				Katunga				
	A	B	C	D	E	F	G		H	I	J
Ga	25	30	25	25	30	20	25	25	15	5	25
Tl	*	*	*	*	*	*	*	*	*	*	*
Sn	*	*	<5?	*	*	35	*	*	*	*	*
Pb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Sc	<10	*	*	<10	<10?	*	*	*	*	*	*
Mo	*	*	*	*	*	*	*	*	*	*	*
Ge	*	*	*	*	*	*	*	*	*	*	<10?
Be	*	*	*	*	*	*	*	*	*	*	*
Ag	*	8	*	*	*	2	*	1	*	1	*
In	*	*	*	*	*	*	*	*	*	*	*

Analyst: R. A. Higazy (spectrographic)
* = Element is considerably less than its limit of sensitivity given in Table one
A = Katungite. Lapilli from tuff, G 21, Katwe crater (Holmes, 1937, p. 207). Analyst: H. F. Harwood
B = Biotite katungite (alnöite). Ejected block, G 56, Katwe crater (Holmes, 1937, p. 207). Analyst: H. F. Harwood
C = Proto-katungite. Ejected block, C 6065, from the rim of one of the oldest craters. Lugazi, Bunyaruguru (Holmes, 1950, p. 784). Analyst: W. H. Herdsman
D = Katungite. Lapilli separated from the first volcanic horizon of the Upper Kaiso Series, C 5945, near M.P. 75 on the Fort Portal Road, N.W. edge of the Bunyaruguru field (Combe and Holmes, 1945, p. 367). Analyst: W. H. Herdsman
E = Katungite. Ejected block, C 3509, from Chamakumba crater, Bunyaruguru (Holmes, 1942, p. 212). Analyst: W. H. Herdsman
F = Kalsilite katungite. Lapilli separated from tuff, C 4012, N.W. rim of Changabe crater, Bunyaruguru (Combe and Holmes, 1945, p. 367). Analyst: W. H. Herdsman
G = Katungite, western flow, C 4407, Katunga (Holmes, 1937, p. 205). Analyst: A. W. Groves
H = Mafurite. Ejected block from the tuffs above the lava sheet of Mafuru, C 6073 (Holmes, 1942, p. 212). Analyst: W. H. Herdsman
I = Olivine-rich ugandite, C 3052. Old rest camp of Kichwamba, adjoining Kachuba crater, Bunyaruguru (Holmes and Harwood, 1932, p. 415). Analyst: H. F. Harwood
J = Olivine ouachitite, C 5844. Ejected block 20 feet below S.E. rim of Katwe crater, Katwe-Kokorongo (Holmes, 1950, p. 780). Analyst: W. H. Herdsman

respectively. The potassic ankaratrites like katungite, have Sr > Ba.

The outstanding features of the trace-element abundances for the potassic ankaratritic rocks are the same as those found for the "K.M.U." series: relatively high Sr, Ba, Rb, and Zr; low Li; Cr > Ni > Co, and La > Y.

Mela-potash nephelinite and mela-leucitite.—Important features in the chemical composition of the mela-potash nephelinite and the mela-leucitite are their low MgO and abundant Na_2O and Al_2O_3, relative to the other volcanic types. This is in accord with their less mafic character. Otherwise, however, they share the main chemical characters of the other volcanic rocks—viz., relatively high K_2O, TiO_2, and P_2O_5, with $K_2O > Na_2O$ and $Al_2O_3 > (K_2O + Na_2O)$. Furthermore, like the ankaratritic rocks, they have CaO > MgO and $(FeO + Fe_2O_3) > MgO$.

The mela-potash nephelinite and the mela-leucitite (Table 3, columns C, D) have trace-element contents strikingly similar. Both have relatively high Sr, Ba, and Rb contents, of the same order as those of the other volcanic types; relatively high Zr content, like all the others except ugandite; and Sr > Ba as in katungite, ankaratritic rocks and ouachitite.

However, they differ conspicuously from all the other types by their extreme impoverishment in Cr, Co and Ni and by having Co > Ni > Cr instead of Cr > Ni > Co.

Volcanic Rocks from Birunga Volcanic Field

Feldspar-free types.—The chemical composition and the trace-element contents of these types are given in Table 4. Olivine melilitite and potash nepheline melilitite resemble the volcanic rocks from the Toro-Ankole field in

TABLE 3.—CHEMICAL COMPOSITION AND TRACE-ELEMENT CONTENTS OF ANKARATRITE, MELA-POTASH NEPHELINITE AND MELA-LEUCITITE

	Ankaratrites		Average ankaratrite	Mela-potash nephelinite	Mela-leucitite
	A	B		C	D
Chemical Analyses					
SiO_2	39.86	35.28	37.57	34.77	37.09
Al_2O_3	8.64	9.84	9.24	10.62	13.03
Fe_2O_3	7.68	6.62	7.15	7.24	7.50
FeO	6.57	6.21	6.39	6.37	5.83
MnO	0.29	0.36	0.33	0.27	0.23
MgO	10.64	9.08	9.86	6.32	5.48
CaO	16.59	14.34	15.47	15.34	14.02
Na_2O	1.30	3.07	2.19	3.58	3.14
K_2O	2.27	5.33	3.80	3.88	4.13
H_2O^+	0.88	2.02	1.45	1.77	2.02
H_2O^-	0.09	0.44	0.27	1.44	0.88
CO_2	none	none	none	2.01	0.90
TiO_2	4.37	6.37	5.37	5.03	4.98
P_2O_5	0.37	0.92	0.65	1.23	1.09
Cl	0.05	...	...	...	...
F	0.06	...	...	...	...
S	...	...	...	...	...
Other constituents	0.40	...	...	...	...
Total	100.06	99.88	99.74	99.87	100.32
Less O	0.04	...	...	...	...
	100.02	99.88	99.74	99.87	100.32
Trace-Element Contents (ppm.)					
Rb	70	270	170	120	180
Li	6	10	8	20	25
Ba	1800	4000	2900	5900	6000
Sr	4000	9800	6900	>1%	>1%
Cr	400	400	400	<1	5
Co	70	80	75	50	40
Ni	100	85	93	15	15
Zr	300	800	550	500	700
La	<30	35	30	<30	<30
Y	<30	30	<30	<30	<30
Cu	90	45	68	250	100
V	250	450	350	350	400
Ga	25	35	30	30	30
Tl	*	*	*	*	*
Sn	*	*	*	*	*
Pb	*	<10	*	*	*
Sc	10?	*	*	*	*
Mo	*	*	*	*	*
Ge	*	*	*	*	*
Be	*	*	*	*	*
Ag	*	*	*	*	*
In	*	*	*	*	*

Analyst: R. A. Higazy (spectrographic)

*= Element if present is in amounts considerably less than its limit of sensitivity given in Table 1

A = Leucite ankaratrite C 5635. Lava occurrence. Lake Mbuga crater, Katwe-Kikorongo (Holmes, 1952). Analyst: W. H. Herdsman. Other constituents include SO_3 0.17; BaO 0.05; and SrO 0.18.

B = Leucite-melilite ankaratrite C 5692. Ejected block from S. rim of Nyaluzigati crater, Katwe-Kokorongo. New analysis by W. H. Herdsman

C = Mela-potash nephelinite C 5566. Ejected block N.N.W. of crater floor S. Nyamununka crater, Katwe-Kikorongo. New analysis by W. H. Herdsman

D = Mela-leucitite C 5545. Loose ejected block from three feet W. rim of South Nymununka crater, Katwe-Kikorongo. New analysis by W. H. Herdsman

TABLE 4.—CHEMICAL COMPOSITION AND TRACE-ELEMENT CONTENTS OF VOLCANIC ROCKS FROM BIRUNGA FIELD

	Feldspar-free types		Feldspar-bearing types				Average feldspar-bearing types	Limburgite G
	A	B	C	D	E	F		
Chemical Analyses								
SiO_2	38.45	36.86	45.66	44.74	44.73	44.86	44.99	44.22
Al_2O_3	13.42	14.97	16.90	18.68	18.18	18.24	18.00	11.56
Fe_2O_3	3.97	3.93	2.20	2.42	1.98	2.20	2.20	2.16
FeO	7.86	7.04	10.35	9.27	9.79	9.53	9.74	8.41
MnO	0.38	0.32	0.21	0.27	0.25	0.24	0.24	0.25
MgO	9.54	4.86	3.98	4.62	4.96	5.19	4.69	13.86
CaO	17.03	15.31	8.97	9.77	9.64	9.29	9.42	13.60
Na_2O	2.52	6.09	3.23	3.05	3.13	2.77	3.06	1.73
K_2O	2.46	5.47	4.23	2.94	3.16	3.16	3.37	1.05
H_2O^+	0.42	0.26	0.25	0.26	0.52	0.46	0.37	0.26
H_2O^-	0.03	0.21	0.06	0.10	0.05	0.22	0.10	0.24
CO_2	none	tr.	0.09	none	none	none	0.02	none
TiO_2	1.94	2.60	3.09	3.02	2.96	3.02	3.02	2.03
P_2O_5	1.33	1.32	0.68	0.53	0.54	0.43	0.54	0.21
Cl	0.06	0.17	0.08	0.09	0.09	0.08	0.09	0.06
F	tr.	0.12	0.15	none	0.01	none	0.04	none
S	...	...	0.07	0.08	0.10	0.10	0.09	0.03
SO_3	0.17	0.14	...	...	...	...	...	...
Cr_2O_3	...	...	0.01	...	...	...	...	...
V_2O_3	...	...	0.06	...	...	...	...	...
NiO	...	...	0.01	...	...	...	...	...
BaO	0.08	0.15	0.09	0.13	0.11	0.11	0.11	0.10
SrO	0.43	0.22	0.08	0.16	0.18	0.15	0.14	0.18
CuO	...	...	0.04	...	...	...	...	...
Total	100.09	100.04	100.49	100.13	100.38	100.05	100.23	99.95
Less O	0.01	0.09	0.08	0.04	0.05	0.04	0.05	0.02
	100.08	99.95	100.41	100.09	100.33	100.01	100.18	99.93
Trace-Element Contents (ppm.)								
Rb	85	300	150	160	180	140	158	50
Li	5	10	9	9	8	18	11	8
Ba	2200	>1%	2800	2600	2000	3000	2600	900
Sr	8000	>1%	4500	5500	4500	5000	4700	1200
Cr	450	<1	10	50	75	70	41	1200
Co	85	70	60	50	40	50	50	75
Ni	100	30	35	30	35	40	35	270
Zr	1000	1100	900	700	650	750	750	400
La	<30	80	<30	<30	<30	<30	<30	<30
Y	60	100	45	40	40	40	41	40
Cu	60	45	35	12	15	15	19	40
V	650	340	320	300	320	350	322	300

TABLE 4.—Continued

	Feldspar-free types		Feldspar-bearing types				Average feldspar-bearing types	Limburgite G
	A	B	C	D	E	F		
Ga	45	35	40	50	50	40	45	8
Tl	*	*	*	*	*	*	*	*
Sn	*	*	*	*	*	*	*	*
Pb	<10	<10	<10	<10	<10	<10	<10	<10
Sc	10	*	*	*	*	*	*	15
Mo	*	2	*	<1?	<1?	<1?	*	1
Ge	*	*	*	*	*	*	*	*
Be	*	*	*	*	*	*	*	*
Ag	<1	<1	*	<1	*	*	*	*
In	*	*	*	*	*	*	*	*

Analyst: R. A. Higazy (spectrographic)
* = Element if present is in amounts considerably less than its limit of sensitivity given in Table 1
A = Olivine melilitite, C 7360, Lwabikari crater, N. of Lake Kivu. New analysis by W. H. Herdsman
B = Potash nepheline melilitite, C 3022. Ninagongo crater. New analysis by Imperial Chemical Industries Limited, Research Department, Billingham, Co. Durham
C = Kivite, C 3030. Lava northern slope of Nyamuragira at 9500 feet. New analysis by Imperial Chemical Industries, Limited, Research Department, Billingham, Co. Durham
D = Leucite basanite (kivite), C 9780. Kituru, new volcano 1948 SSW of Nyamuragira. New analysis by W. H. Herdsman
E = Leucite basanite (kivite) C 9892. Muhubuli 1948. New analysis by W. H. Herdsman
F = Leucite trachybasalt, C 9878. Fissure NW of Kituru 1948. New analysis by W. H. Herdsman
G = Limburgite, c 7347. Nahimbi 1904 between Nyamuragira and Lake Kivu. New analysis by W. H. Herdsman

having relatively high K_2O, TiO_2, and P_2O_5, with $Al_2O_3 > (K_2O + Na_2O)$. However, they differ in the following respects:

(1) Na_2O is slightly more abundant than K_2O. This is related to the preponderance of potash nepheline over leucite in the Birunga types; the ratio Na_2O/K_2O also rises in some of the potash ankaratrites of the Katwe-Kikorongo field.

(2) TiO_2 is relatively low, and perovskite is sparse.

(3) H_2O in these rocks is also lower than in the Toro-Ankole types.

(4) FeO is higher than Fe_2O_3, a feature shared only by ugandite in the Toro-Ankole fields.

It is noticeable that Al_2O_3 is relatively high in the olivine melilitite and potash nepheline melilitite of Birunga, as in the mela-potash nephelinite and mela-leucitite of Toro-Ankole. Moreover, these types have $(FeO + Fe_2O_3) > MgO$, like the ankaratritic rocks.

The outstanding features in the trace-element constitution of the olivine melilitite and the potash nepheline melilitite are:

(1) Great abundance of Ba and Sr. The olivine melilitite has 2200 ppm. of Ba and 8000 ppm. of Sr, while the potash nepheline melilitite possesses as much as >10,000 ppm. of each of these elements;

(2) Moderate contents of Cr and Ni in the olivine-bearing melilitite (450 and 100 ppm. respectively) and paucity of these elements in the potash nepheline-bearing melilitite (<1 and 30 ppm. respectively).

On the whole, the trace-element constitution of the Birunga types under consideration shows the characteristic features of that of the Toro-Ankole—*i.e.*, high Sr, Ba, Rb, and Zr contents and low Li content. Cr and Ni are also relatively low corresponding to the low MgO. It must be mentioned, however, that these types have Y > La, the reverse of the relationship prevailing in the related Toro-Ankole volcanic types.

Feldspar-bearing types.—The kivites and leucitic trachybasalt (Table 4) differ from the olivine melilitite and potash nepheline melilitite in having higher SiO_2 (average, 44.99 per cent) and Al_2O_3 (18.00 per cent); and lower

MgO (4.69 per cent) and CaO (9.42 per cent). Like most of the volcanic rocks of Birunga and Toro-Ankole they are rich in K_2O, TiO_2, and P_2O_5, and have $Al_2O_3 > (K_2O + Na_2O)$. K_2O is not invariably higher than Na_2O, but the relationship $K_2O > Na_2O$, which prevails in the volcanic provinces concerned, holds for the average composition.

The kivitic rocks have $(Al_2O_3 + K_2O + Na_2O) > CaO > MgO$; $FeO > Fe_2O_3$; and $(FeO + Fe_2O_3) > MgO$, like their xenolithic subvolcanic rock, the leucite kentallenite.

The trace-element contents of the four rocks studied are all much alike (Table 4) and share most of the peculiar features characteristic of the two provinces. Sr, Ba, Rb, and Zr are high, and Li is low. It is significant that the average Rb, Ba, Sr, and Zr contents of these kivitic rocks are as high as 158, 2600, 4700, and 750 ppm. respectively, whereas normal ultrabasic and basic types carry negligible or small amounts of each of these elements. Moreover, the average Cr, Co, and Ni contents are relatively low, being only 41, 50 and 35 ppm. respectively. The abundance of V on the other hand is normally high (322 ppm.), exceeding the total Cr + Ni + Co (126 ppm.). As in the Birunga feldspar-free feldspathoidal types, the kivites have Y > La. But the average Ga content (45 ppm.) is relatively high, corresponding to the high average total $Al_2O_3 + Fe_2O_3$ (20.20 per cent).

TABLE 5.—TRACE-ELEMENT CONSTITUTION OF VOLCANIC TYPES FROM TORO-ANKOLE AND BIRUNGA

Rock	Rb	Ba	Sr	Cr	Co	Ni	Zr	V	Ga
Ugandite	XXX	X	X	XXX	XXX	XXX	X	X	X
Mafurite	XXX	XXX	XX	XXX	XX	XX	XX	XX	XX
Katungite	XX	XX	XX	XX	XX	XX	XX	XX	XX
Ouachitite	X	X	X	XX	XX	XX	XX	XX	XX
Ankaratrite	XX	XX	XX	XX	XX	XX	XX	XX	XX
Mela-leucitite	XX	XX	XXX	X	XX	X	XX	XX	XX
Mela-potash nephelinite	XX	XX	XXX	X	XX	X	XX	XX	XX
Olivine melilitite	X	XX	XX	XX	XX	XX	XX	XXX	XXX
Potash nepheline melilitite	XX	XXX	XXX	X	XX	X	XX	XX	XX
Kivite	XX	XX	XX	X	XX	X	XX	XX	XXX
Limburgite	X	X	X	XXX	XX	XX	XX	XX	XX
Average contents in all types (ppm.)	210	4100	6250	535	70	200	765	330	28
XXX	>315	>6150	>9375	>802	>105	>300	>1147	>495	>42
XX	105–315	2050–6150	3125–9375	267–802	35–105	100–300	382–1147	165–495	14–42
X	<105	<2050	<3125	<267	<35	<100	<382	<165	<14

Comparison of the respective trace-element constitutions reveals that kivite (Table 4) has more abundant Rb, Ba, Sr, and Zr, and less Cr and Ni than leucite kentallenite (Table 1).

Limburgite.—Limburgite (Table 4) is similar to kivite in having about the same SiO_2 (44.22 per cent), but it contains lower Al_2O_3, K_2O, and Na_2O; and higher MgO and CaO than kivite. Moreover, limburgite has $CaO > MgO > (Al_2O_3 + K_2O + Na_2O)$ whereas the relationship between these oxides in kivite is $(Al_2O_3 + K_2O + Na_2O) > CaO > MgO$.

The trace-element constitutions of these types (Table 4) differ significantly. Limburgite has higher Cr and Ni, and lower Ba and Sr than kivite. Moreover, in limburgite, V is much less abundant than (Cr + Ni), whereas in kivite V > (Cr + Ni). It should also be mentioned that limburgite has higher Cr, Ni, and Zr than leucite kentallenite (Table 1); the Ba and Sr contents of these two types, however, are almost alike. Otherwise, limburgite shares in one of the main geochemical features which characterizes the volcanic rocks of the

Birunga field—viz., relatively high Rb, Ba, Sr, and Zr with Y > La.

well-known petrologists. The samples represent a carbonate dike, Premier Diamond mine, S.

TABLE 6.—TRACE-ELEMENT CONTENTS OF CARBONATITES AND LIMESTONES

	Carbonatites				Average carbonatite	Limestones		Average limestone
	A	B	C	D		E	F	
Rb	*	*	*	*	*	*	*	*
Li	20	<1	<1	*	5	1	1	1
Ba	290	650	4000	3000	1985	<5	<5	<5
Sr	1000	>1%	>1%	>1%	>7750	<5	300	150
Cr	45	*	*	*	11	3	*	2
Co	50	5	5	5	14	*	*	*
Ni	200	*	*	*	50	*	*	*
Zr	90	70	80	*	60	10	40?	25
La	140	400	700	500	435	*	*	*
Y	45	120	300	100	140	*	*	*
Cu	45	4	7	3	15	4	6	5
V	16	16	30	30	18	6	10	8
Ga	4	*	*	*	1	*	*	*
Tl	*	*	*	*	*	*	*	*
Sn	<5	*	*	<5	*	*	10	5
Pb	<10	<10	10	*	<10	*	*	*
Sc	*	*	*	*	*	*	*	*
Mo	12	1?	1?	3	4	*	2?	1
Ge	*	*	*	*	*	*	*	*
Be	10	*	*	*	*	*	*	*
Ag	8	4	10	2	6	4	1	3
In	*	*	*	*	*	*	*	*

Analyst: R. A. Higazy
* = Element if present is in amounts considerably less than its limit of sensitivity given in Table 1
A = Carbonate dike, Premier Diamond Mine, S. Africa
B = Carbonatite, Spitzkop alkaline complex, Bushveld, Transvaal
C = Carbonatite, Marongwe Hill, Chilwa Island, Nyasaland
D = Sövite, Hartung, Alnö Island, Sweden
E = Limestone, Transvaal System
F = Limestone, M-1, Mansjo, Sweden

Table 5 shows the relative distribution of the different trace elements in all the investigated volcanic types.

TRACE-ELEMENT DISTRIBUTION IN CARBONATITES AND LIMESTONES

Carbonatites and related rocks, as well as limestones, are usually involved in discussions of the genetic problems raised by alkaline rocks. Four carbonatites and two samples of limestones have, therefore, been spectrographically analyzed (Table 6). The carbonatites come from different alkaline complexes which have been studied in detail by Africa (Daly, 1925); a carbonatite from Spitzkop complex, Bushveld, Transvaal (Shand, 1921); another from Marongwe Hill, Chilwa Island, Nyasaland (Dixey, Campbell Smith, and Bisset, 1937); and a sövite from Hartung, Alnö Island, Sweden (Eckermann, 1948). The limestones are from the Transvaal System, S. Africa, and Mansjo, Sweden.

Reference to Table 6 shows that the carbonatites as well as the limestones lack Rb and Ga, and that they have negligible amounts of Li, Cu, or V. Cr, Co, and Ni are relatively low in the carbonatites (average, 11, 14, and 50 ppm. respectively) but negligible in the lime-

stones (2, <1 and <1 ppm. respectively). There are, however, far more outstanding differences. The carbonatites are conspicuously rich in Ba, Sr, La, and Y and have Sr > Ba and La > Y; whereas the limestones have relatively very low Sr content and negligible amounts of Ba, La, and Y. The following contrast is particularly instructive:

Rock	Ba	Sr	La	Y
Spitzkop carbonatite	650	10,000	400	120 ppm.
Transvaal limestone	5	5	*	* ppm.

* Below the limit of sensitivity (30 ppm.)

For carbonate rocks (limestones and dolomites) from Southern Lappland, Sahama (1945) reports Ba, 270 ppm.; Sr, 850 ppm.; La and Y, nil. Noll (1934) gives the range of Sr in limestones as 425–765 ppm.

That limestones are impoverished in Sr, La, and Y, clearly indicates that the susceptibility of these elements to replace Ca decreases remarkably at the relatively low temperatures of formation of such rocks. This corresponds well with the fact that Sr minerals are exceedingly rare in igneous rocks which form at relatively high temperatures but are not uncommon in hydrothermal and sedimentary deposits. In igneous rocks Sr can easily be accommodated into Ca minerals, and so it has no tendency to become concentrated as it has, for example, in low-temperature deposits of celestite and strontianite. The poverty of limestones in Ba can be similarly accounted for. However, according to Rankama and Sahama (1950, p. 483), Ba and K are more easily adsorbed by clays than Sr and Na respectively, because they have correspondingly lower ionic potentials. Most of the Ba in limestones is therefore likely to be present in argillacious impurities. The extremely low contents of Cr, Ni, and Co in limestones can be explained by the paucity of these elements in sea water and their low capacity for replacing Mg (in dolomitic admixtures) at low temperatures.

Petrogenesis

The origin of alkaline rocks in general continues to be debatable; Daly's well-known "limestone assimilation" hypothesis is still under active discussion.

Bowen (1945), in his study of the equilibrium relations in portions of the quaternary system Na_2O–CaO–Al_2O_3–SiO_2, suggested that crystallization differentiation of an initial melilite nephelinite (or melilite-nepheline basalt) magma, produced by limestone desilication of normal mafic magma (or perhaps, in some instances by other means, such as selective resorption of hornblende), might give rise to a series of differentiates such as melilite nephelinite, tephrite, and phonolite. Shand particularly has developed the hypothesis of the desilication of a felsic magma by reaction with limestone to explain the genesis of the nepheline rocks of Sekukuniland, South Africa (1921), and those of the Franspoort Line, Pretoria District (1922), and indeed of alkaline rocks in general (1945). The main petrogenetic process suggested by Larsen (1942)—rather diffidently — to account for the derivation of the alkaline rocks of Iron Hill, Gunnison County, Colorado, was assimilation of marble (itself a carbonatite) by a basaltic magma. Pulfrey (1950), however, considers that the ijolitic rocks near Homa Bay, Western Kenya, were developed chiefly by metasomatic-replacement processes.

Melilite-bearing rocks from Scawt Hill, Co. Antrim, Ireland, were shown by Tilley to be the products of assimilative reactions between chalk and basaltic magma (Tilley and Harwood, 1931). Taljaard (1936), however, rejected the limestone-assimilation hypothesis in his study of the melilite basalts of South Africa. He (Taljaard, 1936, p. 309) assumed that these rocks were crystallization products of an original magma rich in CaO and MgO, poor in SiO_2, Al_2O_3, and alkalies, and that resorption of primary olivine into biotite and of primary pyroxene into magnetite, perovskite, and melilite has taken place prior to complete consolidation.

Leucite rocks from Java have been con-

sidered to be the result of assimilation of limestone by an andesitic lava (Brouwer, 1928). Rittmann (1933), in discussing the evolution of the potassic lavas from the Somma-Vesuvius volcano, assumed that a parental trachytic magma became undersilicated by assimilation of dolomitic limestones. Rittmann suggested that sinking of ferromagnesian minerals, concentration of potash at higher levels, and removal of soda by gases into the wall rock accompanied the assimilation process and so led to the development of the leucite-bearing lavas of that volcano. His mechanism, however, does not account for the abundance of potash in the parental trachyte, which is, after all, the main problem. Wade and Prider (1940) believe that the various leucite-bearing rocks of West Kimberley, West Australia, were derived from the differentiation of a potassic mica-peridotite magma by the early crystallization and removal of olivine. Here again the essential feature is assumed in the "explanation." They thought (Wade and Prider, 1940) that this mode of origin was also applicable to the case of the leucitic rocks of Leucite Hill, Wyoming. More important, they concluded that the limestone-assimilation hypothesis could not explain the peculiar chemical features of their rocks.

Holmes in his account of the petrogenesis of the ultrabasic potassic rocks of the Bufumbira volcanic field has commented adversely on the limestone-assimilation hypothesis. He writes (Holmes and Harwood, 1937, p. 248):

> "One cannot remain satisfied with a hypothesis that appeals to carbonate-assimilation in the Roman Province, when it is found that similar suites of leucitic rocks, and even of melilite-rich rocks, occur in other areas (*e.g.*, South-west Uganda) where there is little or no limestone or dolomite to be assimilated."

In his recent treatment of the petrogenesis of katungite and its associates from South-western Uganda, Holmes (1950) postulates that such rocks are products of reactions between sialic crustal rocks (considered to be the source of Al_2O_3, SiO_2, and above all of K_2O) and carbonatitic magma rich in MgO, CaO, iron oxides, TiO_2, and P_2O_5. Magmatic carbonatites are also regarded as having been involved in the production of the alkaline rocks of the Fen District, Norway (Brögger, 1921); the Chilwa series, Nyasaland (Dixey, Campbell Smith, and Bisset 1937); and those of the Alnö district, Sweden (Eckermann, 1948; 1950a; 1950b).

On the whole, the hypotheses postulated to account for the origin of alkaline rocks may be summarized as follows:

(1) Crystallization differentiation of a basic magma accompanied by resorptive reactions of the primary constituents

(2) Assimilation of carbonate rocks by basaltic or felsic (*e.g.*, trachytic or granitic) magmas

(3) Reactions of magmatic carbonatites and the sialic country rocks

In the case of the rocks studied from Toro-Ankole and Birunga any working hypothesis should provide an adequate explanation for their peculiar assemblage of geochemical characters. Here, we are dealing with rock types which possess the outstanding feature of being ultrabasic and potassic, and enriched not only in Cr and Ni, but also in Rb, Ba, Sr, and Zr. Moreover, some of the rocks—*e.g*, katungite and mafurite—have a relatively high Ga content.

Neither the crystallization-differentiation nor the limestone-assimilation hypothesis can furnish adequate reasons for the above-mentioned geochemical peculiarities. This follows from the results of recent investigations concerning the differential concentrations of various trace elements during the progress of crystallization-differentiation of basic magma (Wager and Mitchell, 1951; Higazy, 1952b)—results which distinctly show that the Rb, Ba, Sr, and Zr contents of basaltic rocks and their differentiates are conspicuously less than those of the volcanic types here under discussion. This very striking contrast indicates that a basaltic parentage for these rocks is practically impossible. This inference is independent of the further very significant fact that true basalts have not been encountered in the Toro-Ankole and Birunga volcanic fields (Holmes and Harwood, 1937). Moreover, it is difficult to believe that basaltic magma, which normally differentiates into residues with increasing SiO_2 as crystallization proceeds, could in some cases give rise to silica-poor differentiates such as the feldspathoid-bearing rocks, unless

certain processes responsible for their desilication, such as assimilation of limestone, were operating. But this would not solve our problem, since basaltic rocks and limestones (Table 6) lack those very trace elements—Rb, Ba, Sr, and Zr—which are present in such surprising abundance in the volcanic rocks under consideration. Differentiation of basaltic magma, with or without assimilation of limestone, cannot, therefore, account for their derivation.

Perhaps, then, these rocks originated as a result of assimilation either (1) of limestone by a felsic magma or (2) of granitic rocks by an olivine basalt magma. On either assumption it is difficult to account for the fundamental regional character of Sr abundance, since none of the materials involved can be regarded as an adequate source. Moreover, the high Cr and Ni contents are left without a source in case (1), and the very low SiO_2 becomes still more difficult to account for in case (2).

That the various volcanic and subvolcanic types of Toro-Ankole are genetically related is quite obvious, since the variations in their major elements are accompanied by similar behavior on the part of their corresponding replaceable trace elements. The recent hypothesis advanced by Holmes (1950) for the explanation of the origin of katungite and its associates advocates that they are products of reaction between magmatic carbonatites and sialic rocks such as granite. The carbonatitic magma is thought to have contributed the cafemic constituents while the granitic types are regarded as the source of the alkaluminous materials. This mode of origin also adequately accounts for the peculiar geochemical features of the rocks concerned. In striking contrast to limestones (Table 6), the analyzed carbonatites contain abundant Sr, La, Y, and Ba; on the other hand, granites are well known to be enriched in Rb, Ba, Zr, and Ga.

On this hypothesis, the high Cr and Ni of some of the studied volcanic types would also have to be supplied by the carbonatites, since granitic rocks are known to have negligible amounts of these elements. The carbonatites actually analyzed, however, do not possess appreciable amounts of either Cr or Ni. This apparent discrepancy disappears, however, when it is realized that the carbonatites met with in the field can represent no more than the relatively Ca-rich portion of the original carbonatitic magma. The latter must also have contained considerable amounts of Mg and Fe (Holmes, 1950, p. 786; 1952, p. 211). During the progress of the complex reactions between carbonatitic magma and granitic rocks, most of the Cr and Ni available would be naturally present in the products developed from the selective silication of the Mg-rich portion of the carbonatitic magma. The residual portion of the carbonatite magma would thus become Ca-rich and would be deficient in Cr and Ni, while, if further reactions with granitic rocks occurred, the resulting products would also be poor in Cr and Ni. The Fe portion of the carbonatite magma was apparently involved during the silication of both the Mg- and Ca-rich portions of this magma since all the rock types generated are rich in iron oxides.

From the facts (a) that members of the "O.B.P." series occur ubiquitously as xenolithic materials in the volcanic types, and (b) that the "O.B.P." material is invariably present in the tuffs and agglomerates, a close genetic relationship between the subvolcanic series and the volcanic types can be regarded as established. In particular, Holmes (1950, p. 783) infers that, at the time of eruptivity, the katungite and proto-katungite magmas existed in an "O.B.P." environment consisting largely of biotite pyroxenite. If the hypothesis of reactions between granite (G) and carbonatitic magma (C) is true, one probable set of complementary products would have been different members of the "O.B.P." series and proto-katungite (P.K.), as indicated by the qualitative equation: G + C → "O.B.P." + P.K.

It is important to keep in mind that there are a great many variables involved in the above equation—compositions, proportions, and physical conditions—and that discussions of particular combinations of these are no more than illustrations of some of the possibilities that can reasonably be envisaged.

The members of the "O.B.P." series were presumably formed under subvolcanic conditions (at relatively low crustal levels) where

the Mg-rich portion of the carbonatitic magma, with abundant Cr and Ni, reacted with sialic (*e.g.*, granitic) material. The former supplied mainly Mg with Cr and Ni, whereas the latter while the production of such a variety as the sphene-rich biotite pyroxenite would require still more. The share of the granitic material in the formation of biotite pyroxenite seems to

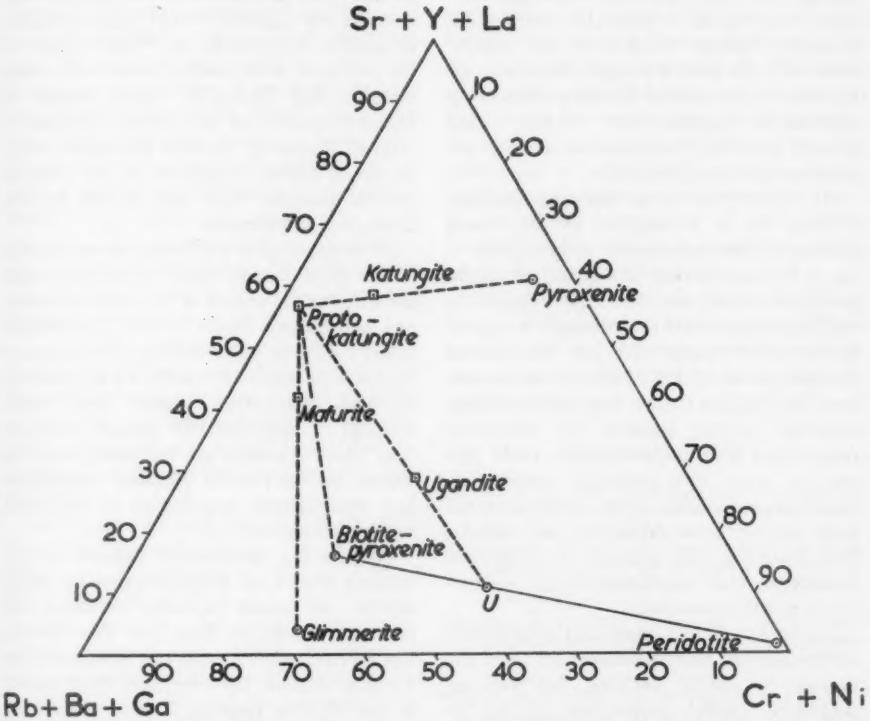

FIGURE 2. RELATIVE PROPORTIONS OF Sr + Y + La, Rb + Ba + Ga, AND Cr + Ni IN THE DIFFERENT VOLCANIC TYPES AND MEMBERS OF THE "O.B.P." SERIES.

Pyroxenite = C 4035; Peridotite = average of C 1963 and C 4034b; Biotite-pyroxenite = average of G 20 and C 2786; Glimmerite = C 4034a; and U = ⅓ peridotite and ⅔ biotite pyroxenite. Katungite = average of all analyzed katungites given in Table 1; Mafurite = C 6073; and Ugandite = C 3052.

contributed Si, Al, and K with Ga, Rb, and Ba, and Zr. The different members of the series, namely peridotite, glimmerite, and pyroxenite, appear to have been formed from correspondingly different proportions of the reactants. The peridotite seems to have developed from reactions between considerable amounts of Mg-rich carbonatitic magma and relatively little granitic material, whereas the formation of glimmerite required reverse quantities of these materials. In the case of pyroxenite, the reactants included much of the Ca-rich portion of the carbonatitic magma, have been greater than that required for pyroxenite and sphene-rich biotite pyroxenite.

Other types such as mela-potash nephelinite, mela-leucitite and potash nepheline melilitite, and possibly kivite, all of which possess relatively low Cr and Ni (as in the case of proto-katungite), can also be considered to develop from essentially similar reactions between Ca-rich carbonatitic magma and granite. However, the proportions of the main reactants would differ in the various cases. Potash nepheline melilitite, for instance, may have had a relatively high supply of the Ca-

rich carbonatitic magma, whereas kivite would require a greater share of sialic reactants and perhaps some basaltic material.

The production of the chief volcanic types—namely, katungite, mafurite, and ugandite—may be attributed to either (1) reactions between the different members of the "O.B.P." series and the proto-katungite magma or (2) reactions of the residual Ca-rich portion of the carbonatitic magma with "O.B.P." and granitic material. Combinations of these two processes are also possibilities.

(1) Figure 2 shows the relative proportions of Sr + La + Y (supplied by the Ca-rich portion of the carbonatitic magma), Rb + Ba + Ga (contributed, like K and Al, by the granitic material), and Cr + Ni (supplied by the Mg-rich portion of the carbonatitic magma) in the chief volcanic types and the different members of the "O.B.P." series. It can be seen from this diagram that, at least arithmetically, reactions between material of glimmerite composition with proto-katungite could give rise to types with mafuritic constitution. Moreover, katungite could similarly result from reactions with pyroxenite, and ugandite from reactions with material of composition U (approximately one-third peridotite and two-thirds biotite pyroxenite).

The other volcanic types such as ouachitite and potash and leucite ankaratrites could also develop by similar reactions, but with appropriately varied proportions of the reactants.

(2) It is also possible that reactions between the Ca-rich portion of the carbonatitic magma, granitic material, and the different members of the "O.B.P." series could give rise to the various volcanic types. This mode of origin is arithmetically similar to that discussed above, since proto-katungite itself is regarded as the result of the reactions between Ca-rich carbonatitic magma and granite. On this alternative assumption, the different reactants would differ in proportion in the various cases. Ugandite (relatively high Mg with abundant ferromagnesian species) would need more of the olivine-rich types of the "O.B.P." series than that required for mafurite or katungite. The proportion of granite would need to be greater for mafurite (relatively high K and Al with abundant kalsilite); while the proportion of the Ca-rich carbonatitic magma would need to be greater for katungite.

It may also be inferred that, as compared with the requirements for mafurite, transitional forms such as leucite mafurite (between mafurite and ugandite) would require a higher proportion of olivine in the "O.B.P." part of the reactants; while melilite mafurite (between mafurite and katungite) would require a higher proportion of the Ca-rich carbonatitic magma. Moreover, kalsilite katungite would require a higher proportion of the reacting granitic material than that needed for the production of katungite.

All these reactions are merely representatives of the great variety which may have taken place during the genesis of the various volcanic and sub-volcanic rocks of the Toro-Ankole fields. Fundamentally, however, the reactants appear to be essentially similar for all the rocks involved—carbonatite magma and sialic material of approximately granitic composition. These reactants are the most promising sources for the peculiar chemical composition and trace-element constitution of the rocks under consideration.

The leading geochemical features of the volcanic types from Birunga, especially kivite, olivine- and potash nepheline melilitites, are essentially similar to those from Toro-Ankole, and therefore their genesis can be explained in a similar manner. However, they differ mainly in the following respects: K is not invariably higher than Na in the Birunga rocks; the latter also possess Y > La, whereas a reverse relationship prevails in the Toro-Ankole rocks. These differences can be attributed either to local variations in the reacting sialic crustal material or incorporation of basaltic material in the different reactions, since basaltic rocks have relatively high Na_2O content and possess the relationship Y > La. Such influence of basic rocks is most marked in the case of limburgite.

The writer does not presume to suggest that alkaline rocks of other districts have necessarily originated in a similar way. It is highly desirable to fill in the lacunae in our knowledge concerning the trace-element contents of such rocks, with a view to test to what extent Holmes' recent hypothesis may prove to be applicable in explaining their genesis.

Conclusions

The chief volcanic rocks of the Toro-Ankole fields (Southwest Uganda) are: katungite (olivine, melilite, and potash-rich glass), ugandite (olivine, augite, and leucite) and mafurite (olivine, augite, and kalsilite). Ouachitite (olivine, augite, biotite, and feldspathoids); and members of the potash ankaratrite–mela-leucitite series (which differ from the mafurite-ugandite series in being conspicuously rich in augite and relatively poor in olivine) also occur. All these types invariably contain perovskite and black ores. Subvolcanic rocks, represented by peridotite, pyroxenites, and glimmerite, are ubiquitous as xenolithic materials in the lava types and fragmental materials in the pyroclasts.

The studied types from the Birunga field (north of Lake Kivu) are: feldspathoid-bearing feldspar-free rocks such as olivine melilitite and potash nepheline melilitite; feldspar-bearing varieties comprising kivite (leucite-basanite) and leucitic trachybasalt; and limburgite.

The volcanic rocks of Toro-Ankole are ultrabasic types relatively rich in K_2O, TiO_2, and P_2O_5 and characterized by having $K_2O > Na_2O$ and $Al_2O_3 > (K_2O + Na_2O)$. The outstanding features concerning their trace-element contents are; relative abundance of elements uncommon in ultrabasic rocks, namely, Sr, Ba, Rb and Zr; normally high contents of Cr and Ni in all types except those which are relatively poor in Mg, namely, mela-leucitite and mela-potash nephelinite; low Li content; and relatively high La and Y with La > Y.

The studied types from Birunga are also relatively rich in K_2O, TiO_2, and P_2O_5, but in these rocks K_2O is not invariably higher than Na_2O. They also have $Al_2O_3 > (K_2O + Na_2O)$ and share with the Toro-Ankole types the peculiar geochemical character of being relatively rich in Sr, Ba, Rb, and Zr. In the Birunga rocks, however, Y > La—*i.e.*, the reverse of the relationship prevailing in Toro-Ankole.

The geochemical characters of the rocks investigated cannot be explained by fractionation of either basaltic or felsic magmas with or without assimilation of limestones, since these sources lack adequate amounts of Sr, Ba, Rb, and Zr. The most promising hypothesis for explaining the genesis of the Toro-Ankole rocks and their geochemical peculiarities is that introduced by Holmes (1950). The volcanic and subvolcanic products are regarded as derivatives of reactions between magmatic carbonatite, which contributed Ca with Sr, La, and Y; Mg with Cr and Ni; Fe with V and Ti; and P; and sialic crustal rocks of approximately granitic composition, which provided Si; Al with Ga; and K with Rb and Ba. The differences in composition of the various products are attributed to respective variations in the proportions of the reacting materials and in the physical conditions under which the reactions took place.

The Birunga rocks originated essentially as did the Toro-Ankole types, but in addition to the sialic reactants basaltic materials may have played a significant part in their production.

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That the various volcanic and subvolcanic types of Toro-Ankole are genetically related is quite obvious, since the variations in their major elements are accompanied by similar behavior on the part of their corresponding replaceable trace elements. The recent hypothesis advanced by Holmes (1950) for the explanation of the origin of katungite and its associates advocates that they are products of reaction between magmatic carbonatites and sialic rocks such as granite. The carbonatitic magma is thought to have contributed the cafemic constituents while the granitic types are regarded as the source of the alkaluminous materials. This mode of origin also adequately accounts for the peculiar geochemical features of the rocks concerned. In striking contrast to limestones (Table 6), the analyzed carbonatites contain abundant Sr, La, Y, and Ba; on the other hand, granites are well known to be enriched in Rb, Ba, Zr, and Ga.

On this hypothesis, the high Cr and Ni of some of the studied volcanic types would also have to be supplied by the carbonatites, since granitic rocks are known to have negligible amounts of these elements. The carbonatites actually analyzed, however, do not possess appreciable amounts of either Cr or Ni. This apparent discrepancy disappears, however, when it is realized that the carbonatites met with in the field can represent no more than the relatively Ca-rich portion of the original carbonatitic magma. The latter must also have contained considerable amounts of Mg and Fe (Holmes, 1950, p. 786; 1952, p. 211). During the progress of the complex reactions between carbonatitic magma and granitic rocks, most of the Cr and Ni available would be naturally present in the products developed from the selective silication of the Mg-rich portion of the carbonatitic magma. The residual portion of the carbonatite magma would thus become Ca-rich and would be deficient in Cr and Ni, while, if further reactions with granitic rocks occurred, the resulting products would also be poor in Cr and Ni. The Fe portion of the carbonatite magma was apparently involved during the silication of both the Mg- and Ca-rich portions of this magma since all the rock types generated are rich in iron oxides.

From the facts (a) that members of the "O.B.P." series occur ubiquitously as xenolithic materials in the volcanic types, and (b) that the "O.B.P." material is invariably present in the tuffs and agglomerates, a close genetic relationship between the subvolcanic series and the volcanic types can be regarded as established. In particular, Holmes (1950, p. 783) infers that, at the time of eruptivity, the katungite and proto-katungite magmas existed in an "O.B.P." environment consisting largely of biotite pyroxenite. If the hypothesis of reactions between granite (G) and carbonatitic magma (C) is true, one probable set of complementary products would have been different members of the "O.B.P." series and proto-katungite (P.K.), as indicated by the qualitative equation: G + C → "O.B.P." + P.K.

It is important to keep in mind that there are a great many variables involved in the above equation—compositions, proportions, and physical conditions—and that discussions of particular combinations of these are no more than illustrations of some of the possibilities that can reasonably be envisaged.

The members of the "O.B.P." series were presumably formed under subvolcanic conditions (at relatively low crustal levels) where

the Mg-rich portion of the carbonatitic magma, with abundant Cr and Ni, reacted with sialic (*e.g.*, granitic) material. The former supplied mainly Mg with Cr and Ni, whereas the latter while the production of such a variety as the sphene-rich biotite pyroxenite would require still more. The share of the granitic material in the formation of biotite pyroxenite seems to

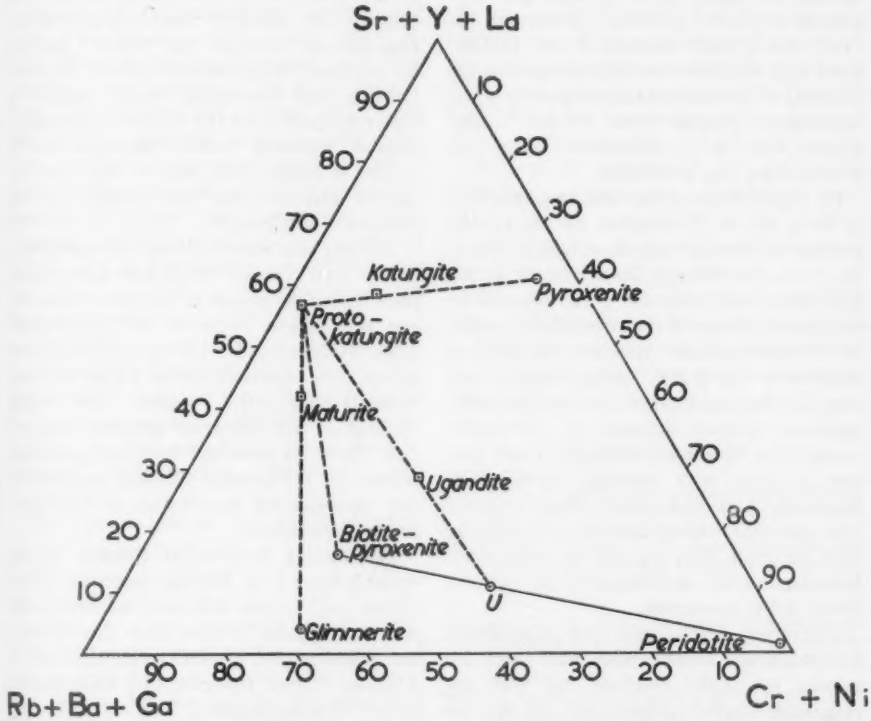

FIGURE 2. RELATIVE PROPORTIONS OF Sr + Y + La, Rb + Ba + Ga, AND Cr + Ni IN THE DIFFERENT VOLCANIC TYPES AND MEMBERS OF THE "O.B.P." SERIES.

Pyroxenite = C 4035; Peridotite = average of C 1963 and C 4034b; Biotite-pyroxenite = average of G 20 and C 2786; Glimmerite = C 4034a; and U = ⅓ peridotite and ⅔ biotite pyroxenite. Katungite = average of all analyzed katungites given in Table 1; Mafurite = C 6073; and Ugandite = C 3052.

contributed Si, Al, and K with Ga, Rb, and Ba, and Zr. The different members of the series, namely peridotite, glimmerite, and pyroxenite, appear to have been formed from correspondingly different proportions of the reactants. The peridotite seems to have developed from reactions between considerable amounts of Mg-rich carbonatitic magma and relatively little granitic material, whereas the formation of glimmerite required reverse quantities of these materials. In the case of pyroxenite, the reactants included much of the Ca-rich portion of the carbonatitic magma, have been greater than that required for pyroxenite and sphene-rich biotite pyroxenite.

Other types such as mela-potash nephelinite, mela-leucitite and potash nepheline melilitite, and possibly kivite, all of which possess relatively low Cr and Ni (as in the case of proto-katungite), can also be considered to develop from essentially similar reactions between Ca-rich carbonatitic magma and granite. However, the proportions of the main reactants would differ in the various cases. Potash nepheline melilitite, for instance, may have had a relatively high supply of the Ca-

rich carbonatitic magma, whereas kivite would require a greater share of sialic reactants and perhaps some basaltic material.

The production of the chief volcanic types—namely, katungite, mafurite, and ugandite—may be attributed to either (1) reactions between the different members of the "O.B.P." series and the proto-katungite magma or (2) reactions of the residual Ca-rich portion of the carbonatitic magma with "O.B.P." and granitic material. Combinations of these two processes are also possibilities.

(1) Figure 2 shows the relative proportions of Sr + La + Y (supplied by the Ca-rich portion of the carbonatitic magma), Rb + Ba + Ga (contributed, like K and Al, by the granitic material), and Cr + Ni (supplied by the Mg-rich portion of the carbonatitic magma) in the chief volcanic types and the different members of the "O.B.P." series. It can be seen from this diagram that, at least arithmetically, reactions between material of glimmerite composition with proto-katungite could give rise to types with mafuritic constitution. Moreover, katungite could similarly result from reactions with pyroxenite, and ugandite from reactions with material of composition U (approximately one-third peridotite and two-thirds biotite pyroxenite).

The other volcanic types such as ouachitite and potash and leucite ankaratrites could also develop by similar reactions, but with appropriately varied proportions of the reactants.

(2) It is also possible that reactions between the Ca-rich portion of the carbonatitic magma, granitic material, and the different members of the "O.B.P." series could give rise to the various volcanic types. This mode of origin is arithmetically similar to that discussed above, since proto-katungite itself is regarded as the result of the reactions between Ca-rich carbonatitic magma and granite. On this alternative assumption, the different reactants would differ in proportion in the various cases. Ugandite (relatively high Mg with abundant ferromagnesian species) would need more of the olivine-rich types of the "O.B.P." series than that required for mafurite or katungite. The proportion of granite would need to be greater for mafurite (relatively high K and Al with abundant kalsilite); while the proportion of the Ca-rich carbonatitic magma would need to be greater for katungite.

It may also be inferred that, as compared with the requirements for mafurite, transitional forms such as leucite mafurite (between mafurite and ugandite) would require a higher proportion of olivine in the "O.B.P." part of the reactants; while melilite mafurite (between mafurite and katungite) would require a higher proportion of the Ca-rich carbonatitic magma. Moreover, kalsilite katungite would require a higher proportion of the reacting granitic material than that needed for the production of katungite.

All these reactions are merely representatives of the great variety which may have taken place during the genesis of the various volcanic and sub-volcanic rocks of the Toro-Ankole fields. Fundamentally, however, the reactants appear to be essentially similar for all the rocks involved—carbonatite magma and sialic material of approximately granitic composition. These reactants are the most promising sources for the peculiar chemical composition and trace-element constitution of the rocks under consideration.

The leading geochemical features of the volcanic types from Birunga, especially kivite, olivine- and potash nepheline melilitites, are essentially similar to those from Toro-Ankole, and therefore their genesis can be explained in a similar manner. However, they differ mainly in the following respects: K is not invariably higher than Na in the Birunga rocks; the latter also possess Y > La, whereas a reverse relationship prevails in the Toro-Ankole rocks. These differences can be attributed either to local variations in the reacting sialic crustal material or incorporation of basaltic material in the different reactions, since basaltic rocks have relatively high Na_2O content and possess the relationship Y > La. Such influence of basic rocks is most marked in the case of limburgite.

The writer does not presume to suggest that alkaline rocks of other districts have necessarily originated in a similar way. It is highly desirable to fill in the lacunae in our knowledge concerning the trace-element contents of such rocks, with a view to test to what extent Holmes' recent hypothesis may prove to be applicable in explaining their genesis.

Conclusions

The chief volcanic rocks of the Toro-Ankole fields (Southwest Uganda) are: katungite (olivine, melilite, and potash-rich glass), ugandite (olivine, augite, and leucite) and mafurite (olivine, augite, and kalsilite). Ouachitite (olivine, augite, biotite, and feldspathoids); and members of the potash ankaratrite–mela-leucitite series (which differ from the mafurite-ugandite series in being conspicuously rich in augite and relatively poor in olivine) also occur. All these types invariably contain perovskite and black ores. Subvolcanic rocks, represented by peridotite, pyroxenites, and glimmerite, are ubiquitous as xenolithic materials in the lava types and fragmental materials in the pyroclasts.

The studied types from the Birunga field (north of Lake Kivu) are: feldspathoid-bearing feldspar-free rocks such as olivine melilitite and potash nepheline melilitite; feldspar-bearing varieties comprising kivite (leucite-basanite) and leucitic trachybasalt; and limburgite.

The volcanic rocks of Toro-Ankole are ultrabasic types relatively rich in K_2O, TiO_2, and P_2O_5 and characterized by having $K_2O > Na_2O$ and $Al_2O_3 > (K_2O + Na_2O)$. The outstanding features concerning their trace-element contents are; relative abundance of elements uncommon in ultrabasic rocks, namely, Sr, Ba, Rb and Zr; normally high contents of Cr and Ni in all types except those which are relatively poor in Mg, namely, mela-leucitite and mela-potash nephelinite; low Li content; and relatively high La and Y with La > Y.

The studied types from Birunga are also relatively rich in K_2O, TiO_2, and P_2O_5, but in these rocks K_2O is not invariably higher than Na_2O. They also have $Al_2O_3 > (K_2O + Na_2O)$ and share with the Toro-Ankole types the peculiar geochemical character of being relatively rich in Sr, Ba, Rb, and Zr. In the Birunga rocks, however, Y > La—*i.e.*, the reverse of the relationship prevailing in Toro-Ankole.

The geochemical characters of the rocks investigated cannot be explained by fractionation of either basaltic or felsic magmas with or without assimilation of limestones, since these sources lack adequate amounts of Sr, Ba, Rb, and Zr. The most promising hypothesis for explaining the genesis of the Toro-Ankole rocks and their geochemical peculiarities is that introduced by Holmes (1950). The volcanic and subvolcanic products are regarded as derivatives of reactions between magmatic carbonatite, which contributed Ca with Sr, La, and Y; Mg with Cr and Ni; Fe with V and Ti; and P; and sialic crustal rocks of approximately granitic composition, which provided Si; Al with Ga; and K with Rb and Ba. The differences in composition of the various products are attributed to respective variations in the proportions of the reacting materials and in the physical conditions under which the reactions took place.

The Birunga rocks originated essentially as did the Toro-Ankole types, but in addition to the sialic reactants basaltic materials may have played a significant part in their production.

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LOWER ORDOVICIAN (CANADIAN) STRATIGRAPHY OF THE MOHAWK VALLEY, NEW YORK

BY DONALD W. FISHER

ABSTRACT

Lower Ordovician (Canadian) strata in the Mohawk Valley, New York, are represented by the Lower Canadian Tribes Hill formation, the Lower Canadian Chuctanunda Creek formation (new), and the Upper Canadian Cranesville formation (new). Perhaps the most striking revelation is the existence of beds younger than Gasconade (Lower Canadian) age lying south of the Adirondack Mountains. The name Tribes Hill is restricted to the limestone phase of the Lower Canadian, and the formation has profitably been subdivided into the Fort Johnson, Palatine Bridge, Wolf Hollow, and Fonda members.

The basal Fort Johnson member consists of slightly sandy dolomisiltite and dolomarenite changing upward through calcitic dolomite to dolomitic calcilutite. This, in turn, grades imperceptibly upward into thin-bedded silty fucoidal dolomite with many intercalations of shaly calcilutite (Palatine Bridge member). A recurrent lithofacies of dolomitic calcilutite constitutes the Wolf Hollow member characterized by an abundant cephalopod-gastropod fauna. Glauconitic calcarenites with a profuse development of gastropods, ribeiroids, hystricurids, and *Clelandia* characterize the Fonda member. Increase in clasticity, together with many shallow-water features, reflects the crustal instability and steady uplift which occurred in late Tribes Hill time. An unconformity, disclosed by truncation of the lower and upper *Ribeiria* limestone zones of the Fonda member, separates the Tribes Hill and Chuctanunda Creek formations.

The Chuctanunda Creek formation is a siliceous dolomite, very cherty, and finer-grained in the upper portion, and presumably the youngest Lower Canadian deposit in the Mohawk Valley. Accurate age assignment is difficult owing to the scarcity and poor preservation of its fossils. An unconformity separates the formation from the overlying Upper Canadian Cranesville dolomite.

The Cranesville dolomite is noncherty, more arenaceous, and lighter-colored than the older Canadian dolomites. It is remarkably barren of fossils, and on the chance discovery of two specimens of *Eccyliopterus* rests its Upper Canadian designation.

A preliminary petrographic study of the rocks suggests that seaweeds supplied adequate magnesium to the lithotope to effect local dolomitization, which gave rise to fucoidal dolomites and mottled limestones.

Restored structural diagrams illustrate that the Lower Ordovician strata were folded prior to Mohawkian (Lowville) sedimentation which makes the unconformity atop the Canadian a major one. This folding was prophetic of more severe structural deformation which occurred subsequently during the Ordovician period.

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Introduction

While mapping the bedrock geology of the Fonda, New York, quadrangle during the summer of 1947, the author became aware that the pre-Mohawkian Paleozoic deposits of the Mohawk Valley required further study. Realizing the importance of the Lower Ordovician Tribes Hill formation in New York stratigraphy, Cushing (1911, p. 136) remarked,

> "The thorough faunal study of this formation, and its proper subdivision and naming, constitute the most important problem which awaits the investigator of the early Paleozoic rocks of New York."

Therefore, the author undertook a stratigraphic and faunal study of the Lower Ordovician sedimentary rocks of the Mohawk Valley during the summers of 1948–1950, while employed as a Temporary Geologist with the New York State Science Service.

This report represents a condensation of the stratigraphic portion of the writer's doctoral dissertation submitted to the faculty of the Graduate School of the University of Rochester. The detailed investigation of the Canadian rocks along the southern margin of the Adirondack Mountains covers portions of eight 15-minute U. S. Geological Survey topographic quadrangles. The lithologic study and stratigraphic interpretations are new, while the paleontological research has been largely confined to bringing the generic names of Cleland's works (1900; 1903) up to date. The results of the paleontologic study will be offered in another paper, but some of the more typical forms are shown on Plate 4. Cursory field examination was carried on in the Champlain, Hudson, and St. Lawrence valleys.

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Grateful appreciation is extended to the faculty and graduate students of the Department of Geology, University of Rochester, who, through stimulating discussion, have aided the writer in the preparation of this article. Special thanks are offered Dr. William R. Evitt II and Dr. William F. Jenks for pertinent advice. Dr. Harold L. Alling kindly furnished the photomicrograph negatives for the petrographic portion of the study.

Historical Sketch

Amos Eaton (1824), the "pioneer geologist" of the Mohawk Valley, never specifically mentioned the strata treated in this discussion. Presumably he included these beds in his "Calciferous Sandrock" or "Transition Sandrock" (p. 72–79). Timothy A. Conrad (1837, p. 162) separated the strata now known as the

Tribes Hill formation from the "Calciferous" as the "Bastard limestone" (a name recorded by Eaton but never defined by him). Oddly enough, in a later report (1839), Conrad did not separate these layers from his "Calciferous Sandstone."

The earliest descriptive work of any consequence on the Tribes Hill was by Lardner Vanuxem (1842, p. 35–38), who separated the beds under discussion from the "Calciferous Sandstone" as the "Fucoidal Layers" because of the presence of abundant seaweeds (fucoids). Vanuxem illustrated for the first time the then-oldest known fossils from the "Third District": "*Orthoceras*" *primigenium*, *Ophileta complanata*, *O. levata*, and an "encrinite" plate. He also mentioned that . . . "an Orthis was found resembling the Testudinarie and a trilobite tail resembling Illeneus". A few years later, James Hall (1847, p. 7–13, Pls. 2, 3) described and figured several fossils from the "Calciferous Sandstone". Most of these came from strata now considered of Tribes Hill age.

In 1899, J. M. Clarke and Schuchert (p. 876) recognized that the Cambrian and Ordovician portions of the "Calciferous" should be differentiated but chose the unsatisfactory locality name Beekmantown for the Ordovician portion, although neither the then-known Tribes Hill nor Fort Cassin faunas were found there. The name "Beekmantown" has been a source of much confusion, and the present writer advocates the discontinuation of the term unless it is relegated to the Middle Canadian (Roubidoux), the only known Canadian rocks outcropping in the vicinity of Beekmantown, New York. Similarly, Clarke (1903, p. 16) proposed the name Little Falls dolomite for the highly magnesian, sparsely fossiliferous phase of the "Calciferous Sandrock" assigning it to the "Champlainic" or "Lower Siluric" and thereby also implying an Ordovician age.

Cleland (1900; 1903) contributed the most valuable paleontologic work in his faunal studies of the "Fucoidal Layers" mainly in the Fort Hunter and Tribes Hill vicinity.

In the *Geology of Little Falls and vicinity*, Cushing (1905) merely placed the strata between the Potsdam and Lowville in the "Beekmantown" formation. This implication automatically assigned the entire "Calciferous" to the Ordovician according to Clarke and Schuchert's definition of 1899. Perplexingly enough, the name Little Falls dolomite appears on the geologic map (dated 1901) for the strata in question when in reality the name was not proposed in the literature until 1903 by J. M. Clarke!

Ulrich and Cushing (1910, p. 99) applied the name Tribes Hill limestone to the previously known "Fucoidal Layers". They reported an unconformity of considerable magnitude at its base, and this, in addition to the fact that the "Fucoidal Layers" possessed a unique fauna unknown in the older Little Falls dolomite (restricted), gave a marked break between the Saratogan and the Beekmantown—the Cambrian and Ordovician of present-day classification. Ulrich regarded the Little Falls dolomite as Lower Ozarkian and the Tribes Hill limestone as Lower Canadian. Their study was based on but two published sections in the Mohawk Valley. At Cranesville, 168 feet was allotted to the Tribes Hill limestone, but later (1938, correlation chart) Ulrich and Cooper assigned only 40 feet to the formation.

On re-examining Cleland's trilobites, Raymond (1910, p. 344) found *Asaphellus* and *Symphysurus*, which "appear to be characteristic of the fauna immediately following the Cambrian". This is the earliest published faunal proof of the Lower Ordovician age of the Tribes Hill limestone.

Cushing and Ruedemann (1914, p. 45) report that the Tribes Hill limestone is absent at Saratoga Springs and vicinity and that the Amsterdam limestone rests directly on the Little Falls dolomite. Recently acquired faunal evidence denies the assignment of an Upper Cambrian age to the dolomite regarded as Little Falls in this area (Fisher and Hanson, 1951, p. 807). This dolomite, named the Gailor, is Canadian and seemingly a facies of the lowermost Tribes Hill formation (Fort Johnson member).

G. R. Megathlin (1938, p. 98) dismisses the Tribes Hill formation thusly

> . . . "the Tribes Hill is not differentiated (on his map) as a separate formation because of the difficulty of distinguishing its limestone beds from those of the overlying formations, and its dolomite layers from those of the underlying Little Falls. Accord-

ingly, the top of the Little Falls has been mapped so as to include most of the dolomite layers, thus leaving the limestone layers with the Trenton-Black River group above."

This is misleading, especially since more than 80 per cent of the dolomite constituting the Canadian of the Mohawk Valley overlies the Canadian (Tribes Hill) limestone which, in turn, rests on supposed Little Falls dolomite. Furthermore, faunally and lithologically, the Canadian and Mohawkian limestones are readily distinguishable. Additional perplexity is introduced when Megathlin states that the Tribes Hill is absent at Canajoharie (p. 99), the . . . "Trenton lies directly on the Little Falls", when actually 125 feet of Lower Ordovician is exposed here.

On the eastern and southern borders of the Adirondack Mountains, Wheeler (1942, p. 521) reported finding the Hoyt limestone overlying the Little Falls dolomite. This disclosure stimulated investigation in the critical Saratoga Springs region (Fisher and Hanson, 1951). Wheeler further advocated that the Tribes Hill formation of the Champlain Valley was separable into the Norton limestone, Fort Ann limestone, and Benson dolomite. The Benson dolomite is assuredly not Tribes Hill but is Middle Canadian (*Lecanospira* zone). Regardless of the preoccupancy of the names Norton and Benson, Wheeler's subdivisions are poorly defined; he gives no type localities or sections, and application to the Lower Ordovician of the Mohawk Valley is untenable. New names for the Mohawk Valley Canadian are therefore necessary. Wheeler's bipartite division of the Canadian into the Tribes Hill and Cassin formations is unsuitable as it rejects the Middle Canadian *Lecanospira* zone from the section.

Geologic Setting

Physiography

The area considered in this paper is the land south of the Adirondack Mountains drained by the Mohawk River and referred to as the "Mohawk Lowland" (Fenneman, 1938, p. 206). This valley is bounded on the south by the Helderberg and Onondaga escarpments, and on the north by the Precambrian Adirondack Mountains. Within this depression the east-west striking Paleozoic beds dip gently south or southwest (averaging 1.5°) so that the extent of north-south outcrop is not great; the rather uniform regional dip carries the older strata below younger formations. Locally, the dips may be steeper close to faults.

Lower Ordovician beds do not occur in a continuous east-west outcrop because widespread normal faulting has dissected the Valley into several horsts and grabens. Most of the major faults are downthrown on the east thus presenting a steplike fault-block pattern. This discontinuous outcrop pattern greatly complicates the tracing of sedimentary beds within the region (Fig. 1).

The drainage is to the east; the Mohawk River with its tributaries presents a crude trellis drainage pattern structurally controlled. As the Canajoharie shale usually occurs on the down-thrown side of the faults, the tributary streams tend to confine their courses to these relatively less resistant layers, roughly parallel to the north-south striking faults.

Pleistocene glacial erosion and deposition have so modified the topography that mapping of the bedrock geology in many places is difficult. Glacial deltas, terraces, outwash plains, kames, drumlins, and moraines are prevalent. Two splendid water gaps occur within the valley; one at Little Falls and the other at the "Noses", midway between Canajoharie and Fonda. At Little Falls potholes puncture the bedrock adjacent to the present channel of the river. In Canajoharie Creek at the southern limit of the village of Canajoharie, the potholes range from a few inches in diameter and depth to 17 feet in diameter and 12 feet in depth.

Generalized Stratigraphy

The generalized stratigraphic column (Fig. 2) and the restored west-east cross section of the Canadian of the Mohawk Valley (Fig. 3) will help to clarify the correlations and better enable the reader to comprehend the problems of sedimentation. The cross section (Fig. 3), however, is drawn as the deposits presumably appeared prior to faulting.

PRE-CANADIAN STRATA: Within the Mohawk Valley proper Precambrian rocks outcrop at three localities: the "Noses"; in the gorge at

74°00'
43°10'
43°05'
43°00'
42°55'
42°50'
74°15'
74°30'
74°45'
MILES
0 1 2 3 4 5
MOHAWK RIVER
CANAJOHARIE
SCHOHARIE CREEK
FLAT CREEK
ONTEORA CREEK
CANAJOHARIE CREEK
GLOVERSVILLE
JOHNSTOWN
AMSTERDAM
FONDA
LITTLE FALLS
HOWARDS MILLS
CANAL
CRUM CREEK
EAST CANADA CREEK
LASELLSVILLE CREEK
WEST CANADA CREEK
DOLGEVILLE
CREEK
MOHAWK
HALF HOLLOW HILL
CANAJOHARIE
ST. JOHNS CHURCH
WELLISTON PALATINE BRIDGE
STONE RAGE
TRIBES HILL
DANDERKILL CREEK
HAGAMAN
DRIVER
CREEK
ROUND
CREEK
CREEK
CREEK

Little Falls; and a quarter of a mile north of Middleville along West Canada Creek. At the "Noses" the dominant rock is a garnet gneiss.

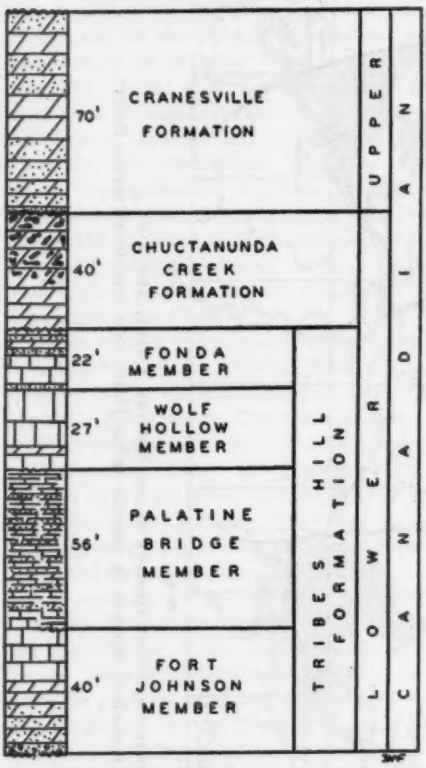


FIGURE 2. GENERALIZED STRATIGRAPHIC COLUMN OF THE LOWER ORDOVICIAN IN THE MOHAWK VALLEY

Minor amounts of igneous rock, such as a trap dike and a sheared pegmatite, also occur here. At Little Falls and Middleville, the rock is predominantly a porphyritic augite syenite.

Overlying the Precambrian and underlying the proven Lower Ordovician deposits is a relatively thick series (ca. 500 feet) of dolomite, sandy dolomite, and some sandstone. Clarke and Schuchert (1899, p. 876) called this the Upper Cambrian Little Falls dolomite. The beds are remarkably barren save for rare *Cryptozoon* and some linguloid brachiopods near the base. The writer has found some trilobite fragments denoting Franconian age in loose pieces of rock that undoubtedly came from this sequence. The upper portion of this dolomite sequence may prove to be Lower Canadian; however, no substantiating faunal evidence has thus far been obtained. The writer found *Schizopea* in the upper few feet of this dolomite sequence, but this is not sufficient evidence for age assignment as this genus occurs in both the Trempealeau and the Canadian although it is more abundant in the Canadian. The Ordovician inference is suggested stratigraphically by two unconformities within the dolomite interval, but their magnitude and extent have not yet been satisfactorily worked out. Owing to the lack of precise information regarding the lower limit of the Canadian in this area, these beds are tentatively referred to the Lower Ordovician.

CANADIAN STRATA: Extending from Little Falls on the west, Lower Ordovician strata outcrop eastward to Hoffmans where they are abruptly terminated by the Hoffmans fault, midway between Amsterdam and Schenectady. Eastward from Hoffmans is a relatively broad area (20 miles) underlain by the Middle Ordovician Schenectady formation, Snake Hill shale, and Normanskill shale. The next Canadian rocks to the east are the Schaghticoke and Deepkill shales and the Bald Mountain limestone (in part)[1] of the Taconic allochthone.

Within the Mohawk Valley the uniform southerly dip causes the most southerly outcrop of Canadian beds to occur about 1 mile south of the river. North of the river, the strata disappear because of offlap and erosion. Variation in the northern limit of outcrop is due partly to the irregularity of the shore line at the time of deposition, and partly to normal faulting which brought the strata into positions where they could either be favorably preserved or more readily eroded.

In ascending order the proven Lower Ordovician deposits of the Mohawk Valley are divisible into three formations (Fig. 2): the Tribes Hill formation, the Chuctanunda Creek dolomite, and the Cranesville dolomite. They aggregate 255 feet.

The name Tribes Hill limestone was pro-

[1] Only the lower portion of the Bald Mountain limestone is Canadian; the upper portion is of Black River and Trenton ages.

posed by Ulrich and Cushing (1910, p. 99) for the beds overlying the Little Falls dolomite and carrying a fauna unknown in the older formation. It was found advantageous to subdivide the Tribes Hill formation both because of notable changes in lithology and, to a lesser degree, limitations in fauna (Fig. 2). These members can easily be traced throughout the Mohawk Valley and should prove useful in future detailed quadrangle mapping. The members range in thickness from section to section due to cumulative local and temporary nondeposition, local truncation of underlying strata, and unequal sedimentation.

The name Chuctanunda Creek formation is proposed for the sequence of medium- to thick-bedded, buff-weathering, blue-gray, medium-grained dolomite which overlies the Tribes Hill formation in the Mohawk Valley. Near the top the beds become siliceous, cherty, and fine-grained. Its meager fauna suggests a Lower Canadian age.

The strata overlying the Chuctanunda Creek formation in the vicinity of Cranesville are post-Lower Canadian (Gasconade) and pre-Lowville (Black River). On the basis of two specimens of *Eccyliopterus* (= *Lesueurilla*), the upper half is tentatively assigned to the Upper Canadian corresponding to the Jefferson City formation of Missouri and the Ogdensburg formation of northern New York. These beds consist of thick- to medium-bedded, light-brown, sandy dolomites and dolomitic siltstones. Beneath these layers is 20 feet of thick-bedded darker dolomites decidedly carbonaceous and containing angular quartz and increasing amounts of feldspar toward the base. The basal stratum is almost invariably a feldspathic sandstone. Faint impressions of *Liomphalus* (?) and *Ophileta* have been observed in these layers, but poor preservation does not permit absolute generic assignment. For lack of more conclusive evidence, these lower, darker, coarse-grained dolomites are lumped together with the lighter dolomites above as the Cranesville formation. Further investigation may produce fossils which may necessitate removal of these darker dolomites from the formation. The Cranesville dolomite is confined to a relatively small area within the lower Mohawk Valley apparently preserved in a syncline (Fig. 3) caused by post-Canadian and pre-Lowville folding.

POST-CANADIAN STRATA: A marked unconformity occurs atop the Lower Ordovician in the Mohawk Valley truncating the strata in such a manner that different stratigraphic units are in contact both above and below this discordance. The oldest post-Canadian rocks observed in this area are of Lowville age and at no place were observed to exceed 25 feet in thickness. However, they do not appear everywhere in their normal stratigraphic position. Owing to the relief of the Canadian erosional surface and post-Canadian folding, many sections show that the Lowville limestone, then the Amsterdam limestone, then successively younger members of the "Trenton" limestone, and finally the Canajoharie black shale rest on the Canadian strata. The Canajoharie with subjacent Canadian have been observed at only one locality, 1 mile south of Sprakers along a small stream tributary to Flat Creek (Pl. 1, fig. 3). The overlying Schenectady formation was not involved in the sectioning for its only relation to Canadian strata is one of fault contact. The pre-Mohawkian surface was very irregular. The hiatus represented embraces a large portion of Canadian time, all of Chazyan time, the bulk of Black River time, and a portion of early Trenton time. In this area, the break atop the Canadian is conceivably only a slight manifestation of a more apparent structural unconformity elsewhere.

Structural Geology

Faulting.—Figure 1 shows the faulting and its association with the stratigraphy of the area. In general, the Mohawk Valley faults are roughly north-northeast striking normal faults usually upthrown on the western side, and increasing in throw toward the Adirondack Mountains. Unless otherwise stated, this applies to all the faults that affect Lower Ordovician strata which are briefly described below. In some instances the displacement given varies from that published (Darton, 1897; Megathlin, 1938).

LITTLE FALLS FAULT: This, the most westerly of the major step faults, has a displacement of about 900 feet. It is through the upthrown

fault block that the Mohawk River carved the gorge at Little Falls. The westernmost exposures of Canadian rocks occur 1 mile southwest of the city just south of New York State highway 5-S.

Caroga Creek at Palatine Church, the Lowville and Trenton limestones dip steeply to the southeast (up to 12°). A quarter of a mile to the east, Lower Canadian dolomite occurs some 40 feet higher. The inferred displacement

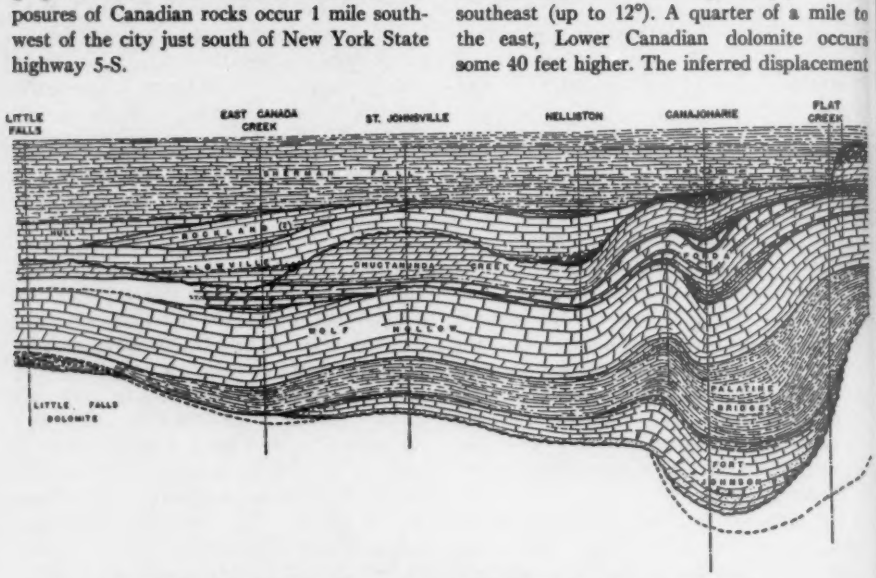


FIGURE 3. RESTORED WEST-EAST CROSS SECTION OF THE LOWER ORDOVICIAN OF THE MOHAWK VALLEY
Drawn as the strata presumably appeared prior to faulting in this region

DOLGEVILLE FAULT: This fault has a displacement of about 450 feet, is upthrown on the east, and forms the eastern boundary of the horst upon which questionable Lower Ordovician dolomites are exposed half a mile south of Dolgeville.

MANHEIM FAULT: This dislocation of some 400 feet can be seen superbly on East Canada Creek, 4 miles west-northwest of St. Johnsville. Almost at the summit of the adjacent falls, 45 feet of Lower Ordovician limestone is exposed.

ST. JOHNSVILLE FAULTS: Two or three faults with variable strikes occur in the vicinity of St. Johnsville; their exact courses are difficult to plot due to the thick glacial cover. The younger Lower Canadian beds are best exposed on the south side of the river, while the older Lower Canadian strata are in scattered field exposures on the north side of the river.

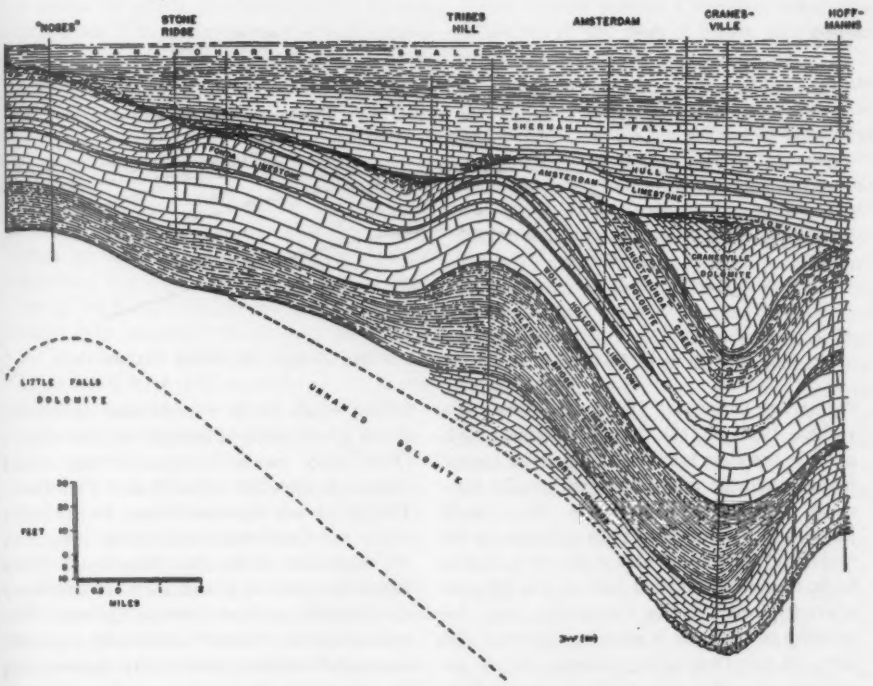
CAROGA CREEK FAULT: This previously undescribed fault, unlike most of the others, is upthrown on the southeast. In the bed of here is 75 feet. This fault may very well be the southern extension of the Ephratah fault.

EPHRATAH FAULT: This dislocation forms the northwestern boundary of the horst which extends eastward to the great Noses fault. The displacement is 70–90 feet near Stone Arabia and about 250 feet in the northeastern portion of the Canajoharie quadrangle. Lower Canadian dolomitic calcilutite may be seen about 1 mile east of Stone Arabia.

NOSES FAULT: This is one of the three most prominent faults of the Mohawk Valley, owing to the spectacular east-facing escarpment produced by the faulting and erosion. Precambrian rocks occur at the base of the upthrown side, and the Lower Ordovician beds appear at the summit forming the tableland to the west. The displacement is approximately 850 feet at the Mohawk River.

STONE RIDGE FAULT: This minor fault was first described by inference (D. W. Fisher, 1948, unpublished report on geology of Fonda, N. Y., quadrangle) as having a dislocation of

100 feet. A recent exposure along New York highway 5-S directly south of the West Shore railroad 2 miles west of Fonda has revealed the fault zone. The splendid contact of the Lower and Middle Ordovician is well shown intermittently westward from this fault for about 2 miles.



TRIBES HILL FAULT: Canadian strata are excellently shown along the western side of this fault which possesses an extremely deviating strike. The displacement is about 250 feet along New York Route 67.

CRANESVILLE FAULT(S): This (These) previously undescribed fault(s) becomes apparent only when strata of Canadian age are traced. In a road cut on New York highway 5-S, south of Cranesville, dragged beds of the basal member of the Tribes Hill formation may be seen. The displacement is 50–70 feet.

HOFFMANS FAULT: This most easterly of the Mohawk Valley step faults probably has the greatest displacement (1600 feet). The bulk of the rocks so widespread on the upthrown side, previously considered Upper Cambrian, are revealed as Lower Ordovician.

Folding.—The Lower Ordovician strata have been subjected to folding. Some of the folding is Mohawkian in age, most of it taking place in Sherman Fall time. The effect of Devonian and later Paleozoic folding on the Ordovician rocks of the Mohawk Valley is unknown. The Helderbergian limestones, rimming the southern margin of the Mohawk Valley, seemingly illustrate broader and more gentle flexures than the Ordovician formations. Careful examination, however, discloses that much of the folding antedates the deposition of the Mohawkian rocks. When the many detailed sections are pieced together we find that the Canadian strata were folded prior to the deposition of the Lowville limestone (Fig. 3). The degree of folding appears to increase in intensity to the east. Conclusive evidence is wanting as to whether the Canadian trend of folding parallels the later folding although along Canajoharie Creek the axis of Trenton folding is

N. 45° E. while the Canadian folding trends N. 20° W.

In the writer's opinion the folding during Canadian time was a forerunner to the normal faulting which has been considered initiated during late Ordovician (Richmond) time (Megathlin, 1938, p. 118). The more intense folds occur in the same localities as the major normal faults, while the minor folds are usually associated with the minor faults. The clastic Palatine Bridge member thins adjacent to the major faults and hence also to the more obvious folds, demonstrating that folding was initiated relatively early during Gasconade time. Instability of the crust is therefore apparent this early in the Ordovician, perhaps closely attendant on earlier crustal disturbances following the Cambrian period.

The trend of the Canadian folding is slightly west of north. In the vicinity of the abandoned quarry on New York highway 67, 2 miles north-northeast of Tribes Hill, and extending south to the area 2 miles east of Fort Hunter, the Chuctanunda Creek dolomite is absent; here the Fonda member of the Tribes Hill formation is the uppermost Canadian unit beneath Mohawkian rocks. This is taken to represent an anticlinal axis for the Chuctanunda Creek dolomite appears within a mile on either flank of this anticlinal area. A similar anticlinal region truncated by the post-Canadian unconformity is observable just east of Stone Ridge where, similarly, the Fonda member is the youngest Canadian represented. Within a short distance east and west the Chuctanunda Creek dolomite appears on the flanks of the anticline. The Cranesville dolomite is preserved in a syncline in a limited area within the lower Mohawk Valley as it is truncated both east and west within 5 miles (Fig. 3). Still another debatable example of Canadian folding which merits consideration is the one shown 1 mile south of Sprakers at the "Devil's Elbow", so named because of the abrupt changes in direction of the flow of Flat Creek. This is the sole exposure known to the writer where the Canajoharie shale rests directly on the Canadian beds; the "Trenton" (Glens Falls) limestone is absent from its customary stratigraphic position between the two. Two wells atop the "Noses" escarpment reputedly penetrated dolomite without first encountering limestone below the black shale. In a tributary to Flat Creek at the "Devil's Elbow" residual Shoreham limestone boulders, containing *Cryptolithus tesselatus*, occur in the basal part of the Canajoharie shale. This suggests that Sherman Fall uplift caused this small area extending eastward to Van Wie Creek to emerge sufficiently to allow the existing Shoreham limestone to be removed except for some scattered residual boulders. Minor upwarping, however, in post-Chuctanunda time may have restricted the Shoreham sea so that only the very latest stage of Shoreham lime was deposited. Boulders of Chuctanunda dolomite up to 17 inches in diameter have been observed 9 feet above the base of the Shoreham limestone along Flat Creek denoting that a ridge of dolomite lay in an exposed position and was eroded not too far from the place where the boulders are now found (Fig. 4).

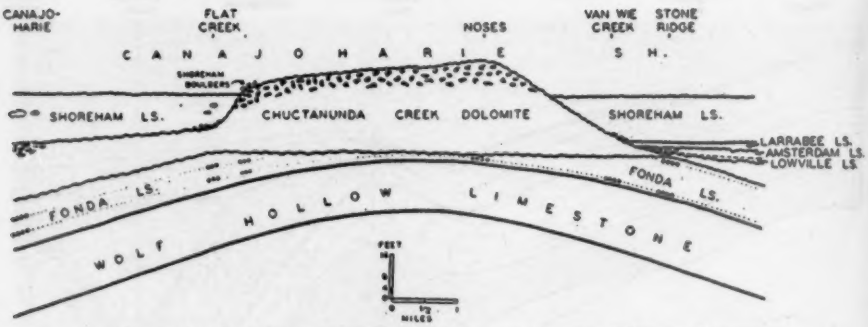


FIGURE 4. MULTIPLE EROSION SURFACES IN THE CENTRAL MOHAWK VALLEY

Jointing.—Jointing in the Lower Ordovician strata has not been studied, but its presence has been noted, particularly in the dolomite and the thick-bedded dolomitic calcilutites. There is no evidence that the jointing afforded a means by which the dolomitization process took place. The joint pattern is similar to that of the older and younger beds, and the problem has been adequately dealt with by Parker (1942).

Lithogenesis

A discussion of the types of lithologies in the Canadian strata of the Mohawk Valley seems advisable in order that the salient points regarding the sedimentation during that portion of the Earth's history can better be understood. The minerals constituting the strata are discussed in order of their abundance. Those which form only a minute portion of the rock are omitted.

LIMESTONE: The limestones of Early Ordovician age within the Mohawk Valley are restricted to the Tribes Hill formation. They range from dolomitic calcilutites, sandy and silty calcarenites, phosphatic-glauconitic calcarenites, to oölitic dolomitic limestone.

Dolomitic calcilutite (Pl. 2, fig. 1) is dominant and forms the bulk of the Wolf Hollow member, about half of the Fort Johnson member, and about a fourth of the Fonda member. Its reticulose or fretwork weathering in which buff-weathering dolomite patches stand out in relief is conspicuous. The calcilutite weathers chalk white. This combination of weathering produces what is commonly referred to as "mottled limestone". Other defining characteristics of this limestone are its dark-gray to blue-black color, its lithographic nature, and subconchoidal fracture. When polished, it assumes a marblelike luster. Absence or rarity of bedding planes for several feet signifies uniform sedimentation. The dolomitic calcilutites are considered chemically precipitated lime muds in which dolomitization was localized.

Calcarenites (Pl. 2, fig. 5) with subangular and rounded calcite grains, with calcite as cement, constitute much of the Fonda member. Minor amounts of calcarenite may also be found in the other members of the Tribes Hill formation. Many beds are not wholly limestone detritus but also contain pyrite, glauconite, and collophane, and varying amounts of quartz sand and silt. These calcarenites reflect local uplifts, and the preponderance of them in the Fonda member heralds a complete withdrawal of the sea at the close of Fonda time and an emergence accompanied by low folding.

The oölitic limestones (Pl. 2, figs. 3, 4) are thin, confined to the Fonda member, and best exemplified by what the writer has designated in his field notes as the "gastropod limestone" because of the profuse development of *Ophileta* and *Liomphalus* (?). It is a medium-grained dark-gray oölitic dolomitic limestone containing much fossil detritus. Pyrite is present but not abundant; glauconite and collophane are absent. Quartz does not exceed 10 per cent and averages much less. This composition conforms to the rock known as "spergenite". The "gastropod limestone" shows the incipient stages of dolomitization very well. Virtually all stages of dolomite replacing calcite may be observed. Spheroidal bodies 0.5–3 mm in diameter, which may represent gastropod excreta, are abundant.

The detrital limestones of the Lower Ordovician of the Mohawk Valley possess many features aside from their textural makeup which stamp them as clastic in origin. Mud cracks, ripple marks, cross-lamination, and pebble conglomerates all denote proximity to shore and deposition in shallow water. Fragmentary, haphazardly arranged, water-worn fossils signify that these strata are allochthonous limestones.

The calcilutites and dolomitic calcilutites are thought to be chemical precipitates in shallow protected environments. The absence of any evidence of agitated waters during Wolf Hollow and upper Fort Johnson times together with rarity of bedding planes indicate quiescence during sedimentation.

DOLOMITE: A wealth of information has been published on dolomite formation. For a fuller knowledge regarding the problem the reader is referred to Van Tuyl (1916), Steidtmann (1917), Skeats (1918), and Linck (1937).

Robert C. Wallace (1913, p. 402–421) was the first to propose the idea that algae were influential in dolomite formation. Therefore, the writer has been especially cognizant of the

intimate relations of *Paleophycus* (fucoid) with dolomitic areas in the Lower Ordovician rocks of the Mohawk Valley. In general, the more abundant the fucoids, the more extensive is the dolomitization. These dolomitic fucoidal beds are splendidly illustrated by the Palatine Bridge member of the Tribes Hill formation. On the other hand, the medium- to coarse-grained, light- to dark-gray, irregular patches in the blue-black calcilutite of the Fort Johnson and Wolf Hollow members are areas that also react chemically for dolomite (by staining). These patches show no preferred orientation; hence if the dolomitization were governed by seaweeds the effect exercised was markedly different from that shown in the fucoidal Palatine Bridge member where the seaweeds are preserved parallel to the bedding.

The writer believes that the dolomite of the Tribes Hill dolomitic limestones formed penecontemporaneously with the chemically precipitated lime mud and certainly preceded the lithification of the lime ooze. As the concentration of the magnesium ions in solution is the determining factor in the process of dolomitization, its localization is suggested as due to magnesium salts liberated from decomposing seaweeds whose remains are plentiful in the strata studied. This would account for the apparent selectivity along predetermined lines which is so characteristic of the mottled limestones (dolomitic calcilutites). This process is considered to have taken place on the bottom of a very shallow epeiric sea in warm quiet water. The relatively high percentage of magnesium ions in the waters which permeated the ooze in the immediate vicinity of the algae would give rise to a purely local mineral transformation which was effected under conditions of temperature and pressure which produced no crystallization in the surrounding lime. The darker color in some of the dolomitized areas is due to the presence of iron salts and carbon, whose source is ascribed to the same origin as the salts of magnesium.

A minor amount of the dolomitic limestone of the Fonda member is clearly a replacement type. In the oölitic dolomitic limestone ("gastropod limestone"), the alteration of the oöids appears to have proceeded independently, and probably in advance, of the alteration of the matrix. Euhedral dolomite grains within the oöids do not extend beyond the oöid bodies (Pl. 2, fig. 3). At least two distinct types of dolomite, probably with different modes of origin, are present in the Canadian of the Mohawk Valley. The medium- and coarse-grained dolomites display perfect rhombs, and the fine-grained conchoidally fracturing dolomites show anhedral grains. Daly (1909, p. 153) suggested that compact fine-grained dolomites were primary in origin. Van Tuyl (1916, p. 391) refutes this. The writer agrees with Van Tuyl. The upper cherty Chuctanunda Creek dolomite is fine-grained, fractures conchoidally, and consists of anhedral dolomite with "nests" of larger grains of subhedral dolomite. It is inferred that the Chuctanunda Creek dolomite was originally a dolomitic calcilutite and that the dolomite was contemporaneous with the calcite. A dissolving action of ground water converted all the remaining calcite to dolomite pseudomorphous after calcite. This indicates definite secondary origin, and the bitextural dolomite denotes two types of origin and two times of dolomite formation.

Some of the dolomite in the lower few feet of the Cranesville formation suggests a clastic origin in that the dolomite rhombs are somewhat rounded. The intimate association of detrital quartz and feldspar with the mechanically worn dolomite supports the clastic origin.

The presence of shallow-water features such as mud cracks, ripple marks, and cross-lamination refutes the assumption by some geologists that dolomites are formed only in deep water.

DETRITAL QUARTZ: Rounded to angular detrital quartz, ranging from sand to silt, is more abundant than was anticipated. Megascopic examination does not reveal the relatively large amount encountered. Some of the layers of the Palatine Bridge member of the Tribes Hill formation have as much as 15 per cent quartz, and locally up to 30 per cent quartz has been noted. The Fort Johnson member is arenaceous, particularly in its lower half where a thin sandstone or siltstone forms the basal layers in many places. Up to 10 per cent detrital quartz occurs in beds of Fonda age; however, less than 1 per cent is found in the Wolf Hollow member and the Chuctanunda dolomite. Owing to the relatively high percentage of clastic quartz in some beds of the Cranesville formation (up to 70 per cent),

the formation may understandably be termed a dolomitic siltstone where only a small section is exposed. This may be due to close proximity to the northern shore where there would probably be an inconsistent supply of detrital quartz.

No change was observed in the east-west distribution of detrital quartz, but the Palatine Bridge member becomes noticeably more arenaceous to the north, which implies a northern land mass for an appreciable amount, if not most, of the quartz.

CHERT: The Mohawk Valley Lower Ordovician chert occurs in a zone, up to 20 feet thick, below a marked erosional surface in the upper part of the Chuctanunda Creek dolomite. In the past, this has been mistaken for the upper Little Falls dolomite. Most of the chert is regarded as epigenetic. Conceivably the silica was precipitated in the zone of weathering by vadose water which tended to follow pre-existing fractures in the strata. Further supporting evidence is the silicified *Clarkoceras* found by Flower in the upper Chuctanunda Creek dolomite. A small amount of nodular chert is present and may be penecontemporaneous. Some of this primary silica may have been partially dissolved and, with an addition from silica-rich waters, redeposited, giving rise to the stringy hackly chert so common in the upper Chuctanunda Creek dolomite.

Some interstitial silica, observed in thin section, probably resulted from redistribution of disseminated silica in meteoric waters following Lower Canadian emergence and erosion. Silicification took place in post-Chuctanunda (Gasconade) and pre-Cranesville (Upper Canadian) time, as the younger strata are noncherty and contain no interstitial silica.

Some quartz crystals were found in the Chuctanunda dolomite, but these were probably formed later.

COLLOPHANE: This amorphous mineral, chemically complex but essentially the phosphate of calcium, occurs as coatings on limestone pebbles and in veinlets in the calcarenite layers of the Fonda and Palatine Bridge members. It commonly is intimately associated with glauconite.

Collophane forms about 7 per cent of some of the calcarenite strata of the Fonda member and is concentrated in the uppermost beds of the Palatine Bridge member, not in excess of 5 per cent. It is yellowish to light brown in thin section and presents a typical mineraloid appearance. It commonly coats fossils or pebbles and is undoubtedly secondary in origin, as some secondary calcite has a collophane coating. The phosphatic-shelled *Lingula clelandi* is most abundant in the phosphatic limestones.

Replacement of calcite by phosphate-bearing waters, during temporary emergence, probably accounts for the collophane in the upper Fonda and Palatine Bridge members.

GLAUCONITE: Glauconite, a complex hydrous silicate of potassium, magnesium, ferric iron, and aluminum, is relatively rare in the rocks studied. The mechanism of the formation of glauconite has been the subject of much debate, and, for a fuller understanding of such, the reader is referred to Takahashi (1939, p. 503–512).

The mineral is found in two zones in the Canadian strata. The lower occurrence is in the upper few feet of the Palatine Bridge member where it is associated with oölitic and spherulitic pyrite, silt, and collophane. The glauconite imparts a pistachio-green tint to the blue-gray limestone and appears to be concentrated in the heavily pyritized regions. The upper zone is within the Fonda member where the glauconite occurs in the phosphatic calcarenites. In both instances the mineral occurs in beds directly beneath stratigraphic breaks.

As both occurrences reveal that glauconite is intimately associated with pyrite, it appears that these minerals were formed in a reducing environment, fouled with hydrogen sulfide and iron, and not well aereated. The faunal content of these beds is additional evidence of abnormal environment, for a diminutive fauna of gastropods and ribeiroids exist in great numbers to the virtual exclusion of other forms. Occasionally a linguloid or trilobite fragment may be found, but cephalopods are wanting for they prefer well-oxygenated waters.

Association with calcarenites, pebble layers, detrital quartz, and indiscriminate arrangement of fossils suggest that glauconization took place in agitated shallow water. Mud (sun) cracks with glauconite and collophane fillings imply that the land was temporarily exposed to the atmosphere. The coexistence of glauco-

nite and primary pyrite directly beneath stratigraphic breaks suggests that the minerals were formed in a littoral or sublittoral environment.

PYRITE: Pyrite, the commonest accessory mineral in the Lower Ordovician strata, occurs throughout the sequence, but its distribution is such that it presents the appearance of being concentrated in two main zones. The lower zone is at the top of the Palatine Bridge member; the upper zone appears in several thin limestone layers, separated by nonpyritic beds, in the Fonda member but for convenience is considered as a single zone.

An abnormally high concentration (up to 45 per cent) of iron sulfide in two such zones indicates deposition in a marine environment where oxygen-rich water was, for the most part, excluded. During sedimentation, temporary barriers brought about transient lagoonal conditions, evidenced by varying thicknesses of the Fonda and Palatine Bridge members, and restricted embayments. This near enclosure of a body of water caused hydrogen sulfide and iron to be concentrated to the point where iron sulfide precipitated. The hydrogen sulfide could have been introduced into the water by decomposing plants (fucoids) and fecal material. Iron could have been weathered from the northern adjacent land and transported into the restricted body of water. The oölitic and spherulitic pyrite (Pl. 2, fig. 2) is primary iron sulfide.

The role, if any, of iron sulfide in the process of glauconization is unknown, but it is significant that the greatest concentrations of each occur together.

HYDROCARBON: A black bitumen mainly interstitial but also in microfractures and in vugs is fairly abundant in certain beds. Physically, it is infusible, has a hardness of 3 to 3.5, conchoidal fracture, and specific gravity of 1.3. Its composition is unknown, as it is extremely resistant to solvents. It is insoluble in the common inorganic acids (slightly soluble in concentrated sulfuric acid), carbon tetrachloride, ether, alcohol, and acetone. Owing to its lustrous black color, it has sometimes been called "anthracite".[2] It is common in the Chuctanunda dolomite but more abundant in the dolomite beneath the Tribes Hill formation.

[2] Recent spectroscopic analysis by Dr. James Dunn of Rensselaer Polytechnic Institute at Troy, New York, reveals that the composition approximates that of high-grade anthracite coal.

STRATIGRAPHY

Tribes Hill Formation

Fort Johnson member (new name).—This basal member of the Tribes Hill formation varies somewhat in its lithologic makeup. The lower half is predominantly dolomite (dolomisiltite and dolomarenite), and commonly a breccia of dolomite cobbles or a sandstone stratum constitutes the base of the member. Between the lower and upper portions of the member is a transition zone of calcitic dolomite and dolomitic limestone, so, if a line were drawn between the two main lithologies, it would have to be an arbitrary one.

The upper half is primarily a thick-bedded, blue-black, dolomitic calcilutite in which the irregular dolomite patches weather out in relief. Previous workers referred to these patches as "siliceous" or "arenaceous" matter. The calcilutite weathers chalk white, while the dolomite weathers buff. Petrographically, the dolomitic calcilutite averages 77 per cent calcite, 23 per cent subhedral to euhedral dolomite, with sparse grains of quartz.[3] Rare grains of pyrite are confined to the dolomitized areas. As gradations from rather pure calcilutite to pure dolomite were found in this and the younger Wolf Hollow member, the value of the percentages may be questionable, but they probably represent the average composition.

The finest exposure of the Fort Johnson member is in the abandoned quarry and railroad cut 2 miles east of Fort Hunter (Pl. 3, fig. 1) where 28 feet is exposed with the base concealed. This is selected as the type locality. Because of the preoccupancy of the name Fort Hunter, the name of the village on the north side of the Mohawk River is applied to this unit.

The Fort Johnson member is the least-exposed unit of the Tribes Hill formation. While its stratigraphic position is adequately shown within the Amsterdam quadrangle, its dis-

[3] The writer employed a modified Rosiwal analysis, utilizing the Wentworth stage, in this and the succeeding petrographic rock analyses in which the average of 10 radial traverses of each rock slice is given.

tribution or even existence west of Fort Hunter is problematical. The intervening sections west to Flat Creek are unrevealing as to its presence. The member is absent atop the Noses escarpment and doubtfully present along Flat Creek but reappears and attains a thickness of 30 feet in the quarry at the eastern limit of Canajoharie. The member is absent westward from St. Johnsville. The Fort Johnson member is overlapped northward by the Palatine Bridge member.

Wherever exposed westward from the Cushing Stone quarry at Cranesville, the Fort Johnson grades upward into the thin-bedded fucoidal layers of the Palatine Bridge member. Eastward from here, there is a marked discordance between the two members because of the relatively rapid eastward thinning of the Palatine Bridge member. As the thickness of the Fort Johnson is not appreciably variable it is inferred that the unconformity reflects uplift during Palatine Bridge time in the Lower Mohawk Valley. This uplift is also manifested in the thinning of the Palatine Bridge member toward the Saratoga Springs region.

Although Ulrich and Cushing (1910, p. 97) report an unconformity at the base of the Tribes Hill limestone, this discordance is not so obvious as implied in the literature. In all but one section (recent exposure along River Road and N. Y. State Thruway at St. Johnsville) where the base of the formation is shown, the relations with the subjacent dolomite are conformable with little or no evidence of erosion. This lack of a well-marked disconformable surface together with the barren aspect of the dolomite make the assigning of the Cambrian-Ordovician boundary most difficult.

In the northeastern sector of the Amsterdam quadrangle, medium-grained blue-gray dolomite up to 90 feet thick with a 6-foot basal white sandstone disconformably underlies the Palatine Bridge member of the Tribes Hill formation. This interval is regarded as the northern thickened extension of the lower half of the Fort Johnson member. When traced into the Saratoga Springs region it proved to be coextensive with the slightly feldspathic, slightly sandy, cherty, gray Gailor dolomite whose basal member is the white Mosherville sandstone (Fisher and Hanson, 1951, p. 806, 807). This formation had previously been termed the Little Falls dolomite in the Saratoga region. It was shown that the meager faunal remains indicate a Lower Ordovician age and that the true Little Falls formation was represented in the Saratoga area by its facies equivalents, the Galway and Potsdam formations. Whether some of the dolomite beneath the Fort Johnson member in the Mohawk Valley should be assigned to the Gailor dolomite is debatable and must await further investigation.

The fauna of the Fort Johnson member is sparse and difficult to sample owing to the compactness of the rock. This list represents the forms encountered. (Relative abundance is indicated by the symbols: a = abundant, c = common, u = uncommon, r = rare.)

Brachiopoda:
- u *Finkelnburgia wemplei* (Cleland)
- c *Tetralobula palmata* (Cleland)

Gastropoda:
- u *Liomphalus* (?) *multiseptarius* (Cleland)
- u *Ophileta* sp.

Cephalopoda:
- r *Clarkoceras* sp.
- r *Ectenolites* sp.
- u *Ellesmeroceras* (?) *primigenium* (Vanuxem)

Trilobita:
- r *Asaphellus gyracanthus* Raymond

Echinodermata:
- r Cystoid plates

Palatine Bridge member (*new name*).—This subdivision is easily distinguished by its relatively large amount of shale and persistent thin-beddedness (Pl. 3, fig. 2). Megascopically, it is a fine- to medium-grained, light blue-gray rock with a "glassy" appearance on fresh fracture. It is difficult to ascertain whether it is limestone or dolomite without using dilute hydrochloric acid. Petrographically, the member can be resolved into two main lithologies: an arenaceous dolomilutite and a slightly silty calcilutite. The extremely fine texture makes a Rosiwal analysis impractical. Calcareous shale intercalations are abundant, and pebble calcarenite layers are especially common near the top of the member. Rounded and, more commonly, angular quartz grains are common, and minor amounts of glauconite, collophane, and pyrite are present. The uppermost few feet of the Palatine Bridge member at the type locality is coarser-grained, unique, but atypical. An analysis of these layers shows 45 per cent pyrite, 28.5 per cent calcite, 18.5 per cent angular quartz, 6.5 per cent collo-

phane, 2.5 per cent glauconite, and rare orthoclase and chalcopyrite. A view of the hand specimen would lead one to expect a larger percentage of glauconite judging by the green color; however, only a relatively small amount appears in thin section. The pyrite is oölitic and spherulitic and presents a "matted" appearance (Pl. 2, fig. 2). Some rare pyritohedrons were observed in hand specimen. Here the beds are poorly stratified in the upper portion of the member.

Exposures of this member are splendid within the valley. The expansive quarry 0.5 mile west of Palatine Bridge is chosen as the type locality. The detailed measured sections disclose that this member has an extremely variable thickness. This may be explained by an inconsistent influx of sediments and local uplifts synchronous with Palatine Bridge sedimentation. The member assumes a somewhat lenslike outline in east-west cross section (Fig. 6). It is absent at Little Falls; is 10 feet thick at East Canada Creek 4 miles west-northwest of St. Johnsville; 26–35 feet thick in and around Canajoharie; 51 feet thick at Flat Creek; 40 feet thick at Tribes Hill, diminishing to 6.5 feet at the Cushing Stone quarry south of Cranesville; 31 feet thick southeast of Cranesville; and 5 feet thick at Hoffmans. The member is at least 25 feet thick in the vicinity of Hagaman and seemingly does not thin northward as rapidly as the other Lower Ordovician units. Thin-bedded fucoidal dolomite, carrying *Ophileta* and strongly reminiscent of the Palatine Bridge member, was observed 0.5 mile south-southeast of the "Petrified Gardens" on the Saratoga quadrangle directly on the Canadian Gailor dolomite. This clarification of the relative stratigraphic positions of these units aids in correlating the Canadian of the structurally separated Mohawk Valley and Saratoga sections.

Numerous evidences of penecontemporaneous faulting and folding within the Palatine Bridge member, together with its varying thickness and clastic nature, suggest an uplift during Palatine Bridge time in the eastern portion of the area. This instability of the crust

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PLATE 1.—STRATIGRAPHIC FEATURES

FIGURE 1. RIPPLE MARKS IN FONDA MEMBER
Along Canajoharie Creek at Canajoharie, N. Y. Ripples strike N. 70° E.

FIGURE 2. ONE OF SEVERAL "HIPPOPOTAMI BACKS"
(DOLOMITIZED *Cryptozoon* BIOSTROME)
In upper Chuctanunda dolomite along Canajoharie Creek.

FIGURE 3. EXPOSURE ALONG TRIBUTARY TO FLAT CREEK
One mile south of Sprakers, showing Mohawkian Canajoharie shale unconformably resting on Canadian Chuctanunda dolomite. Hammer marks contact zone of limonite and calcareous tufa while hat rests on top of dolomite.

PLATE 2.—PHOTOMICROGRAPHS OF SEDIMENTARY ROCKS

FIGURE 1. DOLOMITIC CALCILUTITE (×50), WOLF HOLLOW MEMBER
Polarized light, showing pyrite crystal at contact of dolomite (large euhedra) and calcite (matrix).

FIGURE 2. SPHERULITIC PYRITE (×200), PALATINE BRIDGE MEMBER
Ordinary light; the rosette pattern of the pyrite oöids is in a calcite matrix.

FIGURE 3. OÖLITIC DOLOMITIC LIMESTONE (×50), FONDA MEMBER ("GASTROPOD LIMESTONE STRATUM")
Dolomite rhombs in matrix of carbonaceous material in what appears to be a replaced oöid; the surrounding mineral is calcite.

FIGURE 4. ANOTHER SECTION (×70) OF ABOVE STRATUM
Showing secondary dolomite replacing calcite.

FIGURE 5. GLAUCONITIC-PHOSPHATIC CALCARENITE (×30), FONDA MEMBER
Showing fossil detritus. The prominent trilobite section is presumably of the genus *Hystricurus*.

FIGURE 6. FELDSPATHIC SANDSTONE (OR SUBGRAYWACKE) (×70), BASAL STRATUM OF CRANESVILLE FORMATION
Polarized light; rare microcline in center surrounded by angular to subangular quartz grains.

FIGURE 1

FIGURE 2

FIGURE 3

STRATIGRAPHIC FEATURES

FIGURE 1

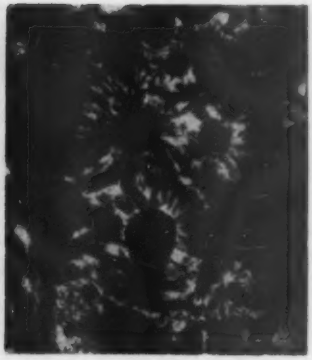


FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

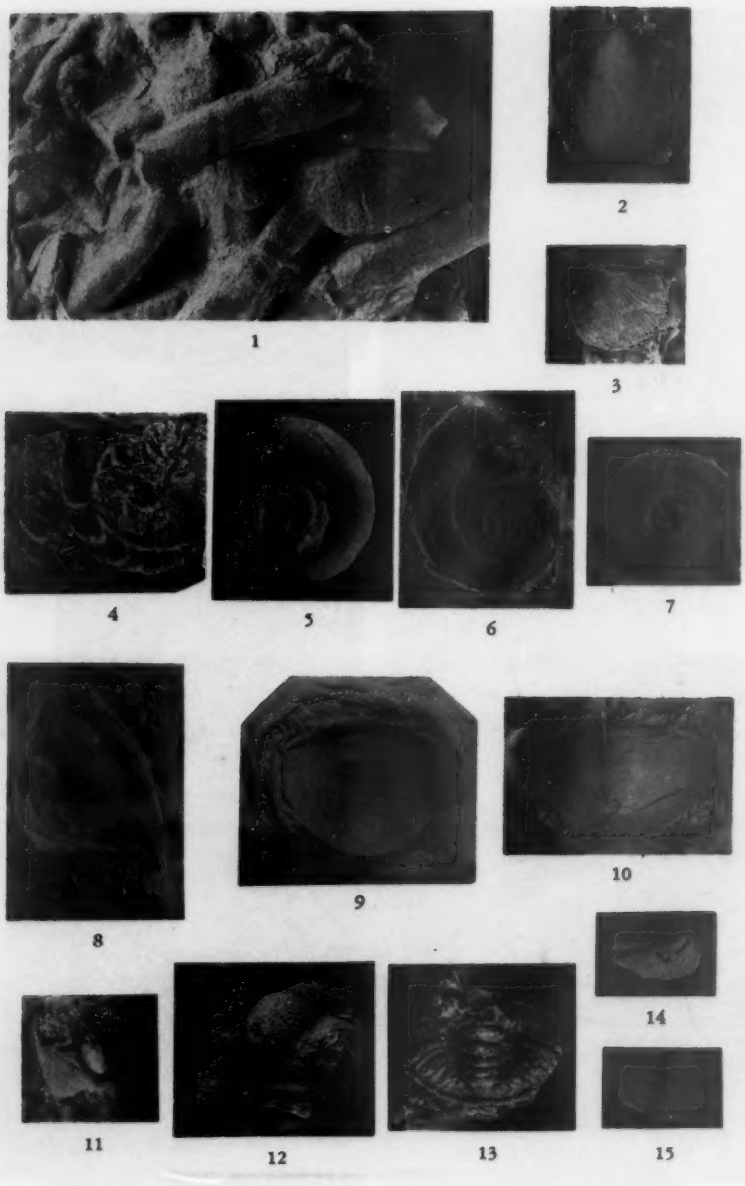
PHOTOMICROGRAPHS OF SEDIMENTARY ROCKS

FIGURE 1

FIGURE 2

FIGURE 3

CANADIAN STRATIGRAPHIC UNITS



TYPICAL MOHAWK VALLEY LOWER ORDOVICIAN FOSSILS

is not reflected in the subjacent Fort Johnson member west of Amsterdam for sedimentation there appears continuous into Palatine Bridge time. It is difficult to delineate the exact contact between the two members west of Amsterdam, and the line is arbitrarily drawn at the top of the highest thick bed of dolomitic calcilutite and the point where the fucoids first appear in abundance.

Presumably, the Palatine Bridge member represents the portion of the original "Calciferous" to which Vanuxem (1842, p. 35) applied the name "Fucoidal Layers". The bedding planes are replete with seaweed remains termed *Paleophycus* by Hall (1847, p. 7). Although the fucoids are not restricted to this member, they are highly diagnostic for they are rare or lacking in the other strata. The fucoidal beds are all more or less dolomitized; in general, the more abundant the fucoids the more intense the dolomitization.

Save for the occurrence of *Paleophycus*, most of the beds of the Palatine Bridge member are sparsely fossiliferous. However, some of the calcarenite layers hold a wealth of trilobite fragments. The other faunal groups are sparsely represented.

Plantae:
- a *Paleophycus irregularis* Hall
- a *P. tubularis* Hall

Brachiopoda:
- r *Lingula clelandi* Ulrich and Cooper
- r *Finkelnburgia wemplei* (Cleland)
- u *Tetralobula palmata* (Cleland)

Gastropoda:
- r *Bucanopsis* (?) sp.
- r *Bucanella calcifer* (Cleland)
- r *Helicotoma uniangulata* (Hall)
- r *Ophileta hunterensis* (Cleland)
- r *O. levata* Vanuxem
- r *Raphistomina obtusa* (Cleland)
- r *Sinuopea* sp.

Trilobita:
- a *Asaphellus gyracanthus* Raymond
- u *Bellefontia* sp.
- c *Symphysurus convexus* (Cleland)

Wolf Hollow member (*new name*).—This, the most widely exposed member of the Tribes

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PLATE 3.—CANADIAN STRATIGRAPHIC UNITS

FIGURE 1. TYPE LOCALITY OF FORT JOHNSON MEMBER OF TRIBES HILL FORMATION

Showing massive white-weathering dolomitic calcilutite; cut on north side of West Shore railroad 2 miles east of Fort Hunter.

FIGURE 2. PORTION OF THE PALATINE BRIDGE MEMBER OF TRIBES HILL FORMATION

At the "Devil's Elbow" on Flat Creek, 1 mile south of Sprakers. Note diagnostic thin-bedded limestones and shale intercalations.

FIGURE 3. LOWER CRANESVILLE FORMATION

Along lower portion of Morphy Creek, 4 miles east of Amsterdam. Left hand of the figure is resting on the Lowville-Cranesville contact. Generically indeterminable *Ophileta*-like gastropods found in ten feet of strata beneath figure. This exposure is now concealed by the N. Y. State Thruway.

PLATE 4.—TYPICAL MOHAWK VALLEY LOWER ORDOVICIAN FOSSILS

Figure
1. *Paleophycus tubularis* Hall, (×1)
2. *Lingula clelandi* Ulrich and Cooper, (×3). Photo supplied by G. A. Cooper; holotype U.S.N.M. 84632.
3. *Finkelnburgia wemplei* (Cleland), (×1.5), pedicle valve
4. *Liomphalus ? multiseptarius* (Cleland), (×1). Showing septate character in cross section, P.R.I. 5373
5. An almost perfect specimen of the same species showing exterior (×1)
6. *Eccyliopterus* sp., (×0.7). Note growth lines and loosely coiled character, Cranesville formation
7. *Ophileta* sp., (×2). Apical view
8. *Symphysurus convexus* (Cleland), (×1). Dorso-lateral view of free cheek
9. Dorsal view of pygidium of above species, (×1). Note absence of brim, segmentation of axial lobe, and faint segmentation of pleural platforms
10. *Asaphellus gyracanthus* Raymond, (×0.5). Note wide brim, indistinct segmentation of faint axial lobe, and smooth pleural platforms
11. *Clelandia parabola* (Cleland), (×2). Oblique anterior view of holotype, P.R.I. 5070
12. *Hystricurus ellipticus* (Cleland), (×2.5). Oblique antero-lateral view of holotype, P.R.I. 5073
13. Dorsal view of pygidium of above species, (×2.5)
14. *Ribeiria nuculiformis* Cleland, (×1.3). Lateral view of right valve; note wavy dorsal keel and short umbonal notch, P.R.I. 5080
15. *Ribeiria ?* sp., (×1.3). Lateral view of left valve of different species and possibly a different genus

Unnumbered illustrated specimens are in the N. Y. State Museum at Albany

Hill formation, owes its excellent exposures largely to its thick-bedded compactness. Typically, it is a very massive, thick-bedded, white-weathering, blue-black dolomitic calcilutite. Spatterings of dolomite appear as raised reticulate markings, weathering buff, against the white weathering of the lime (mottled limestone). Early workers erroneously referred to these dolomite patches as "siliceous matter". Gradations from almost pure calcilutite to pure dolomite exist, but the average proportion of calcite to dolomite is 4:1. There is a deficiency of quartz in this member; a small amount occurs in a single stratum of dolomite, 2–7 feet thick, a few feet above the base of the Wolf Hollow limestone. Pockets of white, yellow, and pink calcite are common in this bed of dolomite. This stratum is clearly traceable throughout the Mohawk Valley and proved most useful in areal mapping.

Maintenance of a fairly uniform thickness is striking. The member is 28 feet thick along East Canada Creek and along Canajoharie Creek in the village of Canajoharie; it shows 19 feet 1 mile east of Stone Arabia with neither the top nor base exposed; is 22 feet thick at the falls on Flat Creek; along New York highway 5-S southeast of Cranesville 27 feet is well shown; and it is 28 feet thick at the type section 2 miles north of Greens Corners on the Amsterdam quadrangle. Owing to the local truncation of the upper beds only 13 feet referable to the Wolf Hollow member occurs in the quarry 2 miles north-northeast of Tribes Hill on New York highway 67. Two abandoned quarries 0.4 mile and 0.6 mile north and northeast of Christman's Corners on the Canajoharie quadrangle display 20 feet capped by Lowville limestone.

There are many fine exposures of the Wolf Hollow limestone from Little Falls to near Galway, Saratoga County. Only the more vital localities are indicated here. The type locality was selected because both base and summit relations are shown, and fossil collecting is good. The name Wolf Hollow is derived from the narrow, north-south trending, trench-like valley following the course of the Hoffmans fault zone which lies 3 miles southeast of the abandoned quarry and the field exposures designated as the type locality. Solution fillings of coarse calcarenite of the overlying Fonda member occur here in the topmost bed of the Wolf Hollow limestone. The Wolf Hollow limestone forms the brink of many of the picturesque waterfalls along the tributaries to the Mohawk River. Notable examples are: the lower falls at Canajoharie along Canajoharie Creek, the falls along Flat Creek 1 mile south of Sprakers, the falls on Van Wie Creek at Stone Ridge, and the falls just north of the Manheim fault on East Canada Creek. Extensive quarrying has brought to light good exposures such as the abandoned quarry 0.5 mile east of Hagaman and the old quarry at the western edge of Canajoharie. Widespread field exposures commonly floor the terrace platforms atop the upthrown fault blocks—*i.e.*, the area west of the Hoffmans, Noses, St. Johnsville, and Little Falls faults.

The Wolf Hollow limestone is conformable upon the Palatine Bridge member in virtually all exposures. A marked lithologic break is apparent, however, and in some sections a slight sedimentary break can be seen. There is a break with the overlying Fonda member which is marked in some sections but indeterminable in others. Probably this should not be regarded as greater than of diastemic proportions.

The fauna of the Wolf Hollow limestone is rich, but specimens are difficult to extract. Accurate identification of species can rarely be accomplished except where favorable conditions of weathering have preserved the more detailed features. The assemblage represents a mixed "cephalopod and gastropod facies" for these two groups exceed the other faunal groups in numbers. The abundant nautiloids, the scarcity of trilobites, and the completeness of specimens indicates environmental conditions somewhat different from those prevailing in the earlier Palatine Bridge sea or later Fonda sea. In order of decreasing abundance, the characteristic nautiloids are *Clarkoceras*, *Ectenolites* (= *Ectenoceras*), *Ellesmeroceras*, *Eremoceras*, and *Walcottoceras*. *Ophileta*, *Liomphalus* (?), *Sinuopea*, and *Gasconadia* are the typical gastropods. The following fossils were obtained in this study:

Plantae:
r *Cryptozoon* sp.
Brachiopoda:
c *Finkelnburgia wemplei* (Cleland)
r *Nanorthis* (?) *holiensis* (Cleland)

Gastropoda:
u *Bucanella calcifer* (Cleland)
r *Euconia floridensis* (Cleland)
c *Gasconadia putilla* (Sardeson)
a *Liomphalus* (?) *multiseptarius* (Cleland)
r *Ophileta complanata* Vanuxem
u *O. hunterensis* (Cleland)
c *O. levata* Vanuxem
u *O.* sp. A
u *Raphistomina obtusa* (Cleland)
r *Schizopea* sp.
c *Sinuopea turgida* (Hall)
Cephalopoda:
c *Clarkoceras* sp. A
c *C* sp. B
c *Ectenolites gracilis* (Cleland)
u *Ellesmeroceras clelandi* (Ulrich, Foerste, Miller)
c *E.* (?) *primigenium* (Vanuxem)
c *Eremoceras mohawkense* (Ulrich and Foerste)
u *Walcottoceras* sp.
Trilobita:
r *Asaphellus gyracanthus*-Raymond
r *Symphysurus convexus* (Cleland)
Echinodermata:
u Cystoid plates

Fonda member (new name).—This most fossiliferous member of the Canadian strata of the Mohawk Valley has a varied lithology. Silty, sandy, phosphatic calcarenites and dolomitic calcilutite are conspicuous. The remainder of the member consists of pebble conglomerates, calcitic dolomite, steel-gray dolomisiltite and oölitic dolomitic limestone. Petrographic analysis shows the calcarenite layers average 78 per cent calcite, 12 per cent quartz, 7 per cent collophane, 1.5 per cent glauconite, 1 per cent dolomite, and 0.5 per cent pyrite. The quartz is angular and primarily of silt size. Many cross sections of haphazardly arranged fossils were observed. Some of the fossiliferous limestone beds of the Fonda member exhibit a higher degree of dolomitization than others—*i.e.*, the "gastropod limestone". This oölitic dolomitic limestone, replete with *Ophileta* and *Liomphalus* (?), is composed of 70 per cent calcite, 22 per cent dolomite, 4.5 per cent quartz (largely interstitial silica), and 3.5 per cent pyrite and hematite. Many oöids showed spastolithic forms, and one oöid observed has a pyrite nucleus.

The Fonda member has a very spotty distribution and variable thickness due to inconsistent influx of sediments, many diastemic breaks caused by several minor uplifts during Fonda time, and erosion preceding deposition of the overlying Chuctanunda Creek dolomite. It is absent at Little Falls, 7 feet thick at East Canada Creek, 17 feet thick along Canajoharie and Flat creeks, and thins to 4 feet atop the Noses escarpment. It then thickens eastward to 15 feet at Stone Ridge and reaches its maximum thickness of 22 feet at the western edge of Tribes Hill. It then thins abruptly to 9 feet in Amsterdam and is absent eastward until it reappears with a thickness of 5 feet, 2 miles north of Greens Corners, the most easterly exposure. It offlaps the Wolf Hollow limestone and is absent north of Stone Arabia. The abandoned quarry 0.5 mile east of Stone Ridge is chosen as the type locality.

Microscopic analysis reveals the Fonda member to be essentially an allochthonous limestone. Supporting evidence is the fragmental and water-worn condition of its fossils, the association of silt, sand, and pebbles, and the calcarenite type of limestone. The deposits represent those of an epineritic or perhaps even a sublittoral environment. The ripple marks (Pl. 1, fig. 1), cross-lamination, and pebble conglomerates signify agitated water sufficiently shallow to develop strong bottom turbulence. The association of glauconite, according to Takahashi (1939, p. 503), also denotes agitated water, for he believes that glauconization occurs in rough water under reducing conditions and in an environment periodically exposed to the atmosphere. The occurrence of mud cracks filled with glauconite would tend to substantiate this. The Fonda member is construed as the closing phase of a cycle of deposition that was predominantly lime and hence genetically can be regarded as the uppermost member of the Tribes Hill formation.

The Fonda sea heralded the invasion of new forms such as *Hystricurus*, *Clelandia*, and the ribeiroids. The ribeiroids are unique to the calcarenite layers. The prolific development of these forms in rather narrow zones probably can be ascribed to a selectivity to definite ecological conditions. Ribeiroids undoubtedly preferred an environment devoid of well-aereated water for the beds in which they are so abundant are high in iron sulfide. Gastropods are, similarly, abundant in these calcarenite strata almost to the exclusion of the cephalopods. The calcarenite layers may be designated as a "ribeiroid" or "ribeiroid-gastropod" facies in contrast to the biofacies of the calcilutite beds which is a "cephalopod" facies.

Two *Ribeiria* faunizones have been distinguished in the field. The lower zone is at or near the base of the member, while the upper zone occurs at varying horizons within the member, depending on the section under consideration. The interval between the two zones is thickest at and west of Tribes Hill. The two *Ribeiria* limestones converge westward and eastward suggesting minor uplifts in these directions. These lines of contemporaneity illustrate the differential uplift during Fonda time, and the truncation of these time lines discloses an unconformity with the superjacent Chuctanunda Creek dolomite (Fig. 5).

The calcarenite layers are considered a "ribeiroid" biofacies; however, the nautiloid *Walcottoceras*, and to a lesser extent *Ectenolites*, have been found in these layers in some abundance. The ecological conditions postulated would exclude nautiloids from such an environment. As the specimens are always so badly water worn that specific identification is almost impossible, it is conceivable that *Walcottoceras* and *Ectenolites* did not actually live in this "ribeiroid" environment but that the conchs were deposited in lime sand after death, having washed in after they were extracted from an unconsolidated lime mud elsewhere by excessive wave action. The small size of the conchs would allow this to happen. If this be so, then we have here the existence of a thanatocoenese.

In addition to the ribeiroids, *Ophileta levata*, *Bucanella calcifer*, and *Raphistomina obtusa* occur in great profusion in the sandy and silty calcarenite layers. Fragmentary trilobite remains are common in the calcarenite beds but rare in the calcilutite layers. In contrast, with the exception of *Walcottoceras* and *Ectenolites*, all the nautiloids observed were confined to the calcilutite beds. This list represents the forms found in the Fonda member. Those preceded by an asterisk (*) seemingly are restricted to the member.

Brachiopoda:
- c *Lingula clelandi* Ulrich and Cooper
- a *Finkelnburgia wemplei* (Cleland)
- r *Nanorthis* (?) *holiensis* (Cleland)

Gastropoda:
- a *Bucanella calcifer* (Cleland)
- r *Euconia floridensis* (Cleland)
- c *Gasconadia putilla* (Sardeson)
- a *Liomphalus* (?) *multiseptarius* (Cleland)
- r *Ophileta complanata* Vanuxem
- c *O. hunterensis* (Cleland)
- a *O. levata* Vanuxem
- u *O.* sp. A
- a *Raphistomina obtusa* (Cleland)
- r **Rhachopea* aff. *typica* Ulrich and Bridge
- r *Schizopea* sp.
- u **Sinuitopsis subovatus* (Cleland)
- r *Sinuopea turgida* (Hall)

Cephalopoda:
- u *Clarkoceras* sp. B
- u *Ectenolites gracilis* (Ulrich, Foerste, Miller)
- r *Ellesmeroceras* sp.
- u *Eremoceras mohawkense* (Ulrich and Foerste)
- c *Walcottoceras* aff. *obliquum* Ulrich, Foerste, Miller, Unklesbay

Trilobita:
- a *Asaphellus gyracanthus* Raymond
- c **Clelandia parabola* (Cleland)
- c **Hystricurus ellipticus* (Cleland)
- u **H.* sp. A
- c *Symphysurus convexus* (Cleland)

Archaeostraca Incertae Sedis:
- a **Ribeiria nuculitiformis* Cleland
- u **R.* (?) sp. A
- u **R.* (?) *turgida* Cleland

Echinodermata:
- u Cystoid plates

Chuctanunda Creek Formation (New Name)

The Chuctanunda Creek dolomite is named for the fine exposure along North Chuctanunda Creek within the city of Amsterdam. The formation is entirely dolomite although the type of cement varies. The upper half of the formation is a siliceous dolomilutite; the silica cement has so impregnated the dolomite that the rock mass behaves physically as chert. The upper half is fine- to medium-grained, brownish gray to blue gray, markedly cherty, and with much interstitial silica. The chert is mainly stringy or hackly, but nodular chert is also present, and bedded chert has occasionally been found. Dark-blue to gray, variegated noncherty coarse dolomarenite, locally laminated, forms the lower half of the formation. Small amounts of silt and angular sand are present. Carbonaceous material may locally be abundant—*i.e.*, along Canajoharie Creek the percentage of carbonaceous matter reaches 10 per cent. The bitextural dolomite has been discussed in a previous chapter. An analysis of the lower half of the Chuctanunda dolomite shows 88 per cent dolomite, 4.5 per cent detrital quartz, 3 per cent carbonaceous matter, 2 per cent calcite (secondary), 1.5 per cent silica, 0.5 per cent pyrite, and rare glauconite. The upper half averages 75 per cent dolomite, 24 per

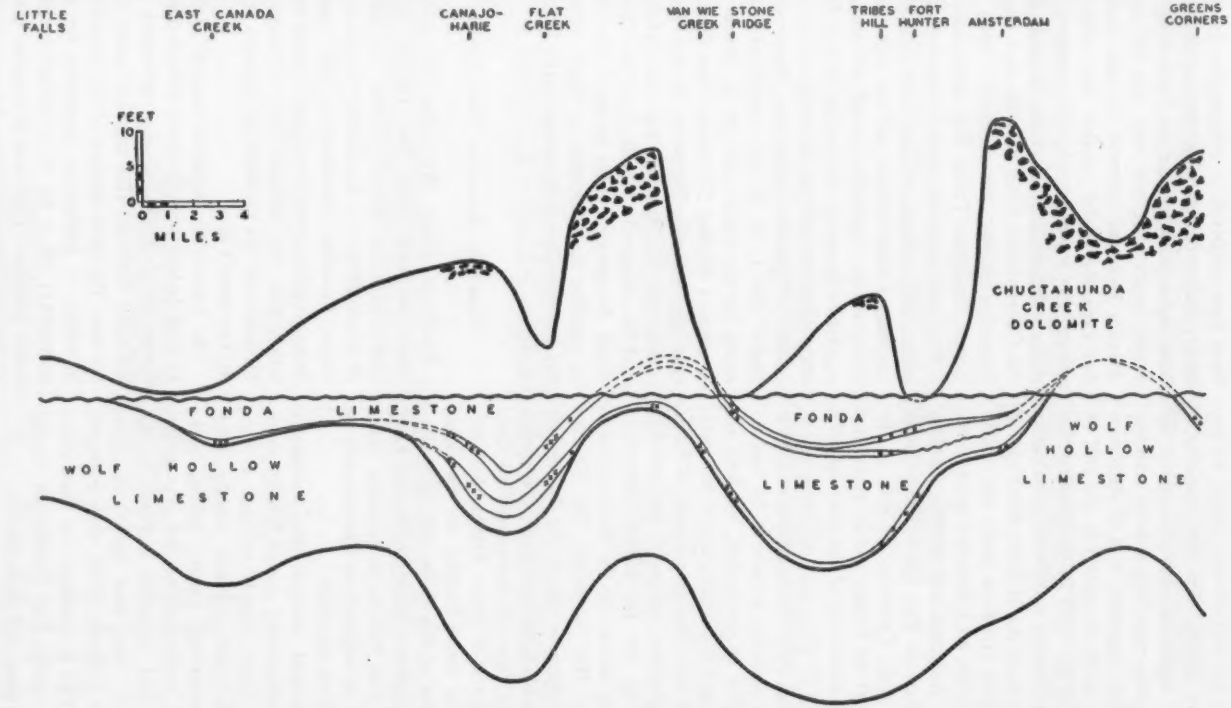

FIGURE 5. UNCONFORMABLE RELATIONS OF CHUCTANUNDA CREEK DOLOMITE AND THE UPPER LIMESTONE MEMBERS OF THE TRIBES HILL FORMATION

Upper and lower *Ribeiria* limestones, designated by x's, are regarded as lines of contemporaneity

cent silica, 0.5 per cent detrital quartz, 0.5 per cent secondary calcite, and rare hematite.

Widespread exposures occur throughout the valley. Among the most favorable for examination are the field exposures west of Pattersonville 0.1 mile south of route 5-S, the cliff on the west side of the valley in Wolf Hollow, the sections along Morphy and Swartztown creeks on the south side of the Mohawk River east of Amsterdam, field exposures north and northeast of Cranesville, an abandoned quarry midway between Hagaman and Manny Corners, a small tributary to Flat Creek 1 mile south of Sprakers, along Canajoharie Creek at the southern edge of the village, and an abandoned quarry on the south side of the river opposite St. Johnsville.

The thickness varies from section to section reflecting the erosional surface at its top. At the type locality in Amsterdam, the beds are 40 feet thick, and this seems close to the maximum. East of Fort Hunter and east of Stone Ridge post-Canadian truncation has bevelled the dolomite so that the Middle Ordovician limestones rest directly on the Fonda member of the Tribes Hill formation. The Chuctanunda Creek dolomite offlaps the Tribes Hill formation in a northward direction. It is absent north of Little Falls and also along East Canada Creek. North of Stone Arabia, the Lowville limestone rests directly on the Wolf Hollow member of the Tribes Hill formation. Whether the cherty dolomite below the Lowville at Rock City Falls in the Saratoga quadrangle should be regarded as Chuctanunda or Gailor dolomite is uncertain.

Strong erosional cavities are excellently shown in an abandoned quarry 2 miles south of Hagaman. Chert, largely residual, is haphazardly mixed with dolomite cobbles, large crystals of secondary calcite (white, pink, yellow, black), carbon, pyrite, and sand grains. Innumerable field exposures eastward to the Hoffmans fault have been classed as Little Falls dolomite (Jeffords, 1950, map; Simpson, 1952, map). This is erroneous for these dolomite layers overlie the fossiliferous Lower Ordovician Tribes Hill formation.

A slight hiatus at the base of the Chuctanunda Creek dolomite illustrates that sufficient time ensued for the Tribes Hill formation to have been subjected to compression or, more likely, differential warping, forming low folds, with subsequent erosion so truncating the Fonda strata that not only was the upper *Ribeiria* limestone removed in some sections but even the entire member was eroded in others. The writer regards this structural evidence sufficient to warrant the designation of the Chuctanunda Creek dolomite as a distinct formation resting unconformably upon the Lower Canadian Tribes Hill formation.

It is problematical whether it is correct to assign this dolomite to the Lower Canadian. Its meager fossil remains are not well enough preserved nor diagnostic enough to formulate a positive statement concerning its age. Faint impressions of *Ophileta*, *Liomphalus* (?), dolomitized *Cryptozoon* resembling "hippopotami backs" (Pl. 1, fig. 2), and fucoids have been found by the writer, and R. H. Flower has obtained a silicified *Clarkoceras* from the chert near the summit. *Clarkoceras* is not known above beds of Gasconade age, and failure to find the diagnostic Middle Canadian (Roubidoux) *Lecanospira* fauna prompts the writer to consider the Chuctanunda Creek dolomite the youngest Lower Canadian in the Mohawk Valley.

Cranesville Formation (New Name)

Strata of Lower Ordovician age younger than Gasconade have been thought to be absent from the Mohawk Valley. The finding of *Eccyliopterus* (= *Lesueurilla*)[4] supports the Upper Canadian classification. This meager faunal evidence would seemingly suggest correlation with the Jefferson City formation of Missouri and the Ogdensburg dolomite of the St. Lawrence Valley.

The Cranesville formation consists of thin- to thick-bedded grayish-brown dolomites alternating with sandy and silty dolomites and dolomitic siltstone. Thin seams of sandy shale are rare. The basal stratum of the formation is invariably a feldspathic sandstone (or subgraywacke) (Pl. 2, fig. 6), a typical sample of which contains 73 per cent subangular quartz, 11 per cent interstitial silica, 8.5 per cent feld-

[4] Verified by the late Dr. Josiah Bridge, letter of April 6, 1950.

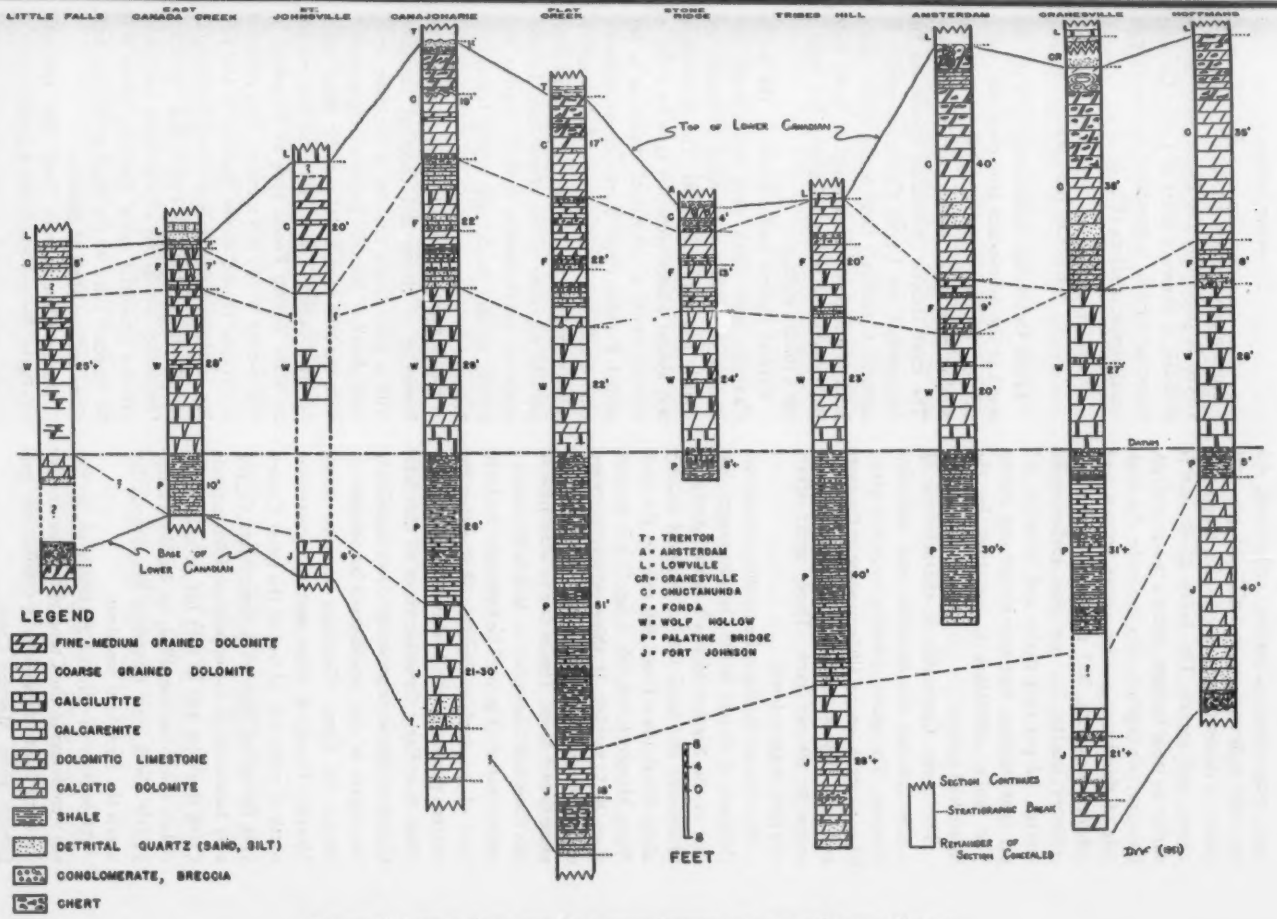

FIGURE 6. LOWER CANADIAN COLUMNAR SECTIONS IN THE MOHAWK VALLEY
Datum is the Wolf Hollow-Palatine Bridge contact

spar (plagioclase, microcline, orthoclase), 4.5 per cent carbonaceous material, 2.5 per cent calcite or dolomite, and rare biotite, magnetite, zircon, and garnet. The lower 25–30 feet is darker on fresh fracture, being a coarse-grained, blue-gray, variegated, silty dolomite. An analysis of this lower portion shows 70 per cent euhedral dolomite, 20.5 per cent angular and splintery quartz, 7.5 per cent carbonaceous matter, 1.5 per cent pyrite and hematite, 0.5 per cent feldspar, and rare biotite and zircon. The darker coloration is imparted by the interstitial carbon.

The upper Cranesville is characterized by coarse light-tan dolomarenites and dolomitic siltstone. The purer dolomite beds run about 95 per cent dolomite, while in some of the more quartzose layers the percentage of dolomite drops to 30 per cent. These upper strata weather cream-colored.

The Cranesville dolomite reaches a maximum thickness of 70 feet in the Cushing quarry just east of the Niagara-Mohawk power station at Cranesville and is 67 feet at the type locality along Swartztown Creek 0.6 mile to the east. Along Morphy Creek (Pl. 3, fig. 3) it is no more than 30 feet thick. It thins rapidly eastward and westward so that its east-west extent is no more than 5 miles. This is due to truncation of the Canadian folds prior to Middle Ordovician sedimentation (Fig. 3). The formation is absent west of Amsterdam denoting that either the western portion of the Mohawk Valley was uplifted after Early Canadian times so that later Canadian seas were prevented from inundating the region or else pre-Mohawkian erosion removed the Upper Canadian deposits. Along Morphy Creek, 4 miles east of Amsterdam south of route 5-S, 23 feet of the lower Cranesville formation rests on a dolomitized *Cryptozoon* biostrome of the uppermost Chuctanunda Creek dolomite and in turn lies beneath 4 feet of Lowville limestone (Pl. 4, fig. 2). Along Canajoharie Creek, this biostrome lies directly beneath the Shoreham limestone.

Aside from the proven *Eccyliopterus*, no fossils were found in the Cranesville dolomite save for some faint impressions of *Ophileta*-like gastropods along Morphy Creek.

Columnar Sections

Since much needless repetition would be involved in presenting the 28 measured sections in detail, a summary chart of Lower Canadian columnar sections is presented to illustrate the stratigraphic relations (Fig. 6).

Geologic History

Lower Ordovician sedimentation in the area south of the Adirondack land mass was similar to that of the Upper Cambrian (Croixian). Similar rock types signify similar lithotopes. The most ancient Ordovician epeiric sea that transgressed the Upper Cambrian surface inundated a relatively large region quite rapidly. Lack of an appreciable amount of clastic material reflects the rather featureless low relief of the Croixian surface.

Typical marine fossils attest to the marine Canadian seas which were undoubtedly very shallow, probably not exceeding 20 fathoms and usually less than 5 fathoms. The environment was almost wholly epineritic save for a few instances where a sublittoral condition is suggested. Fucoids, ripple marks, cross-lamination, mud cracks, and the presence of glauconite all denote shallow water; the mud cracks imply periodic exposure to the atmosphere. Intraformational conglomerates indicate waters sufficiently shallow to develop strong bottom turbulence.

Tribes Hill time was characterized by the formation of clastic and chemical limestones with a subordinate amount of dolomite, which undoubtedly formed penecontemporaneously with the lime ooze. Local periodic minor uplifts occurred during Tribes Hill time and reached an acme during Fonda time as evidenced by calcarenites within this member. This crescendo of periodic crustal unrest resulted in low folding, emergence, and erosion which developed an unconformity atop the Tribes Hill formation. Oscillatory conditions of regression and transgression produced many diastems, which is to be expected since we are dealing with the nearshore feather edges of deposits.

During Chuctanunda Creek time, dolomitic calcilutite formed which the leaching action of ground water altered to relatively pure dolomite

during the epi-Chuctanunda emergence. The Tribes Hill-Chuctanunda interval could not have been very long for there is no evidence of any appreciable relief at the base of the Chuctanunda formation.

Regional uplift in post-Early Canadian time caused a withdrawal of the seas, and silicification preceded Cranesville sedimentation. This unconformity atop the Lower Canadian is evidenced wherever these strata are exposed in New York State.

Medial Canadian seas were excluded from the area south of the Adirondacks because following early Canadian uplift that area had not yet been worn down sufficiently to allow the seas to transgress. A slight invasion of the Late Canadian sea allowed the sandy and silty dolomites of the Cranesville formation to form in the lower Mohawk Valley. Early Ordovician time closed with folding, which increased in intensity to the east and resulted in uplift of sufficient magnitude to prevent epeiric sea transgression until Lowville time.

Adirondackia (Kay, 1937, p. 289), a land mass north of the sedimentary area, was a positive area shortly after Canadian time. It consisted of Precambrian gneisses, quartzite, marble, gabbro, and anorthosite, covered by widespread, but patchy, Upper Cambrian sandstones, sandy dolomite, and dolomite.[5] Several outliers of Upper Cambrian deposits overlain by Mohawkian strata lie well within the peripheral border of the Adirondack Mountains. In none of these have Lower Ordovician rocks been observed. At least two conditions can be postulated to explain this: either Early Ordovician seas did not cover the Adirondacks, or if the Canadian deposits were laid down they were removed preceding Lowville sedimentation. The writer prefers the second condition which suggests that the emergence of Adirondackia was concurrent with post-Canadian uplift in the Mohawk Valley. This uplift gave rise to the Adirondack Arch (Kay, 1936, p. 390), a southerly directed peninsula of Adirondackia. Evidence presented earlier in this article supports the inference that this sedimentary barrier was effective during Lowville deposition and therefore was initiated earlier than Kay had suggested.

Reworking of the Upper Cambrian strata, which fringed the Laurentian land mass (including Adirondackia), provided the material for part of the Canadian deposits. No evidence was found to support the existence of a land mass to the east during Canadian time. If there were such a land mass it must have existed considerably farther east and was not influential in Canadian sedimentation in New York.

Canadian topography did not become peneplaned until Lowville time when shallow embayments existed along the southern Adirondackia shore. Canadian relief was still apparent during Amsterdam time judging by the patchy distribution of that formation, and some islands of Canadian dolomite remained until Shoreham (Middle Trenton) time. Large boulders of Canadian dolomite are common in the Shoreham limestone which implies that the older dolomite lay in an exposed position where it was susceptible to erosion. An unconformity, probably local, occurs between the Shoreham limestone and the Canajoharie shale in the central Mohawk Valley. This uplift caused the thin veneer of Shoreham limestone to be stripped away leaving only some residual limestone boulders on the older cherty Canadian dolomite. The effect of these multiple erosion surfaces is shown diagrammatically in Figure 4.

Correlations of the Canadian rocks of the Mohawk Valley with other sections in New York State and areas beyond the State will be discussed in another paper.

[5] Kay (Private communication) doubts that the Adirondacks had any Precambrian rocks exposed until medial Trenton time.

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